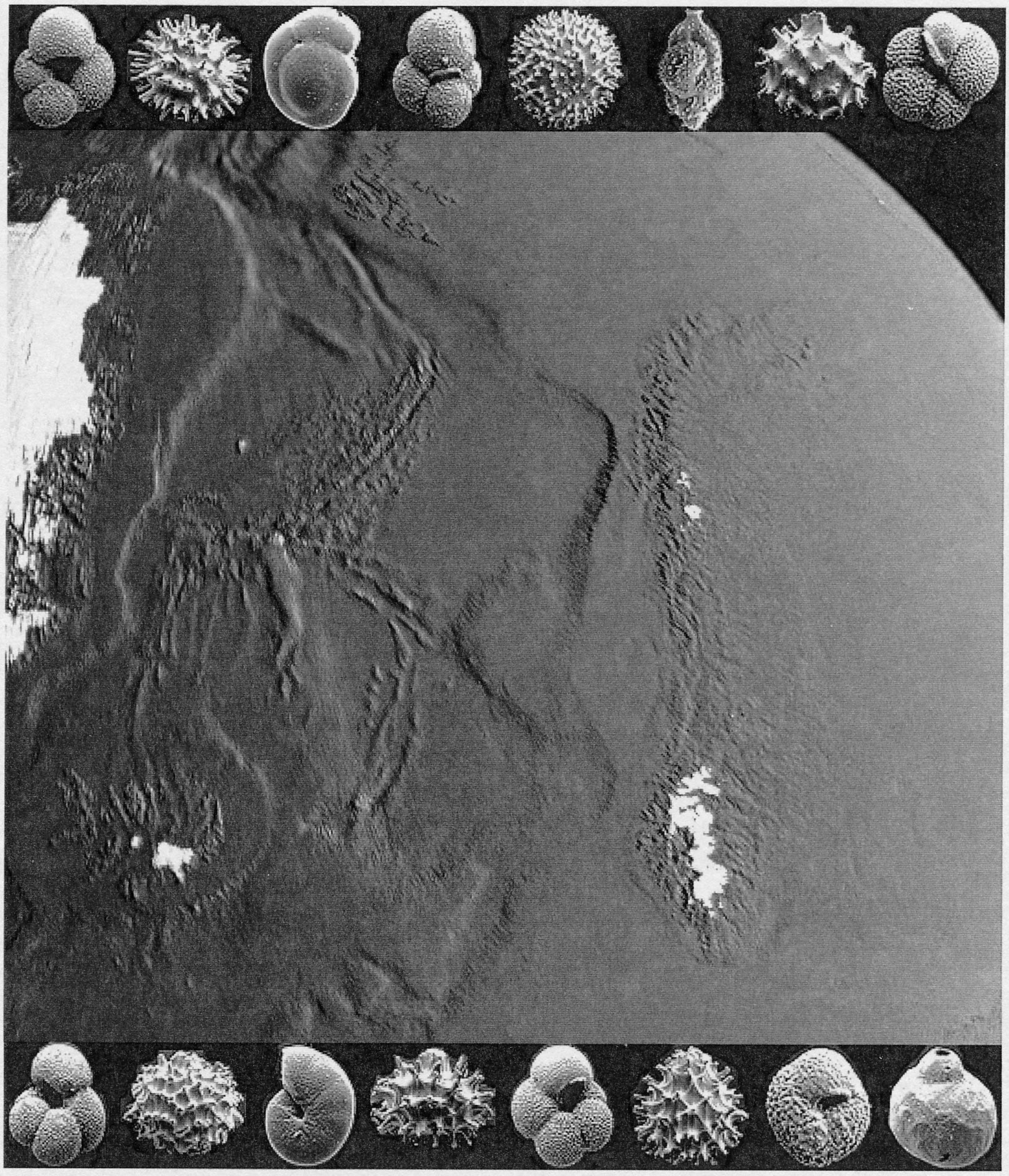
Late Cainozoic stratigraphy of the Norwegian continental shelf

Tor Eidvin



Thesis submitted for the Dr. philos. degree
Department of Geology/The faculty of mathematics and natural sciences,
University of Bergen, Norway 2000

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Contents

Preface

This dissertation has been prepared for the degree of doctor philosophiae at the University of Bergen. The thesis comprises seven papers, six of which are published, while one is a manuscript in press. I am first author to these papers and have contributed with biostratigraphical analyses, lithological examinations, integration of stratigraphical data and synthesising the work. The main contributions of my co-authors have been seismic interpretations, regional discussions, analyses of dinoflagellates, radiolarians (Bjørnøya West area) and agglutinated foraminifera (Svalbard Margin).

All my co-authors are gratefully acknowledged. I will also acknowledge the benefit of discussions to Fridtjof Riis, Eystein Jansen, Jenö Nagy, Yngve Rundberg and Robert Williams which have been very important support throughout the work. Furthermore, I would like to thank Finn Moe, Bjørg Ruus, Sigrun Torrissen and Inger M. Våge for their excellent technical support and Rune Goa, Astrid Larsen and Per Torgersen for drafting and help with the illustrations. I should also like to extend my thanks to other persons involved in various parts of this research, including everyone who is acknowledged in the individual papers. I am especially grateful to the Norwegian Petroleum Directorate (NPD) for supporting and funding various projects, and allowing to publish the results. I am also very grateful to Norsk Hydro ASA and Statoil for supplying many sidewall cores.

The papers are arranged such that the synthesis paper comes first, following this the papers dealing with the different regions are arranged from south to north.

List of papers included in the thesis

1: Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H. and Grogan, P. (2000). The Upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and North Atlantic. *Marine and Petroleum Geology 17*, 579-600.

2: Eidvin, T., Riis, F. and Rundberg, Y. (1999). Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). *Norsk Geologisk Tidsskrift 79*, 97-127.

3: Eidvin, T. and Rundberg, Y. (In press). Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidsskrift.*

4: Eidvin, T., Brekke, H., Riis, F., and Renshaw, D. K. (1998a). Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N - 68°N. *Norsk Geologisk Tidsskrift 78*, 125-151.

5: Eidvin, T., Jansen, E. and Riis, F. (1993). Chronology of Tertiary fan deposits of the western Barents Sea: implications for the uplift and erosion history of the Barents Shelf. *Marine Geology, 112*, 109-131.

6: Eidvin, T., Goll, R. M., Grogan, P., Smelror, M. and Ulleberg, K. (1998b). The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area). *Norsk Geologisk Tidsskrift 78*, 99-123.

7: Eidvin, T. and Nagy, J. (1999). Foraminifer biostratigraphy of Pliocene deposits at Site 986, Svalbard Margin. In Raymo, M. E., Jansen, E., Blum, P. and Herbert, T. D. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 162*: College Station, TX (Ocean Drilling Program), 3-17.

Introduction

The research documented in this dissertation has its origin in the disappointing results of oil exploration in the Barents Sea in the 1980s, when petroleum explorers realized that deep erosion of the shelf was the cause to this problem.

When the exploration drilling for hydrocarbons in the Barents Sea started in the early 1980s, it soon become clear that the shelf area had been subject to extensive uplift and erosion in the Tertiary to Pleistocene time. Regional mapping in the mid 1980s delineated the erosional products as sedimentary wedges along the western and northern margin of the Barents Shelf (Nøttvedt et al., 1988; Rassmussen and Fjeldskaar, 1996). Where Cainozoic erosion prevailed the explorations yielded only gas discoveries and structural traps showed evidence of late spillage and leakage of hydrocarbons (Nyland et al., 1992). As a consequense, the magnitude, timing and causes of uplift became a matter of considerable interest and debate both in the industry and the academia.

Wells 7117/9-1 and 7117/9-2 on the Senja Ridge, drilled in 1982 and 1983 respectively, were the first exploration wells to penetrate the large fan off Bjørnøyrenna on the western margin of the Barents Sea. Major uncertainties were inherent in the earlier biostratigraphic datings of the fan deposits in these wells. Different industry consultants arrived at widely diverging ages varying from Eocene to Miocene for the sediments at the fan base. This problem also affected the published literature; e.g. Spencer et al. (1984) concluded that at the base of the sediment wedge a major hiatus is developed. Sediments above this hiatus appeared to range from Miocene to Late Pliocene, which led the authors to conclude that the lower boundary of the fan could be intra-Oligocene in age. Nøttvedt et al. (1988) proposed a mid-Oligocene age for the base of the fan. A re-dating of the fan deposits was required, and this research started at the NPD in 1988. The work was in progress when preliminary data from the scientific results from the Leg 104 drillings on the Vøring Plateau became available (Eldholm, Thiede, Taylor et al., 1989), and it facilitated a correlation with boreholes close to Barents Sea margin where the biostratigraphic and lithostratigrapic units were age calibrated by means of paleomagnetic data (Spiegler and Jansen, 1989; Jansen et al., 1988). The results from the re-dating were published by Eidvin and Riis (1989) and Eidvin et al. (1993; paper 5 in this thesis), and showed that the fan deposits in the wells were of Late Pliocene and Pleistocene age and had a glacial origin.

The main reason for the earlier dating discrepancies originated from the strong influence of re-deposited material in sediments comprising the fan. The proposed relatively young ages were, however, initially challenged by numerous workers in the industry, and by Vorren et al. (1990 and 1991), Richardesen et al. (1993) and Knudsen et al. (1993) suggesting that the lower unit of the wedge off Bjørnøyrenna is of Middle to Late Miocene age based on downlap on oceanic crust and magnetic anomalies. A late Pliocene-Pleistocene age for all the late Cainozoic sedimentary wedges along the entire western margin of The Barents Sea is later supported in numerous papers including Mørk and Duncan (1993), Sættem et al. (1994), Fiedler and Faleide (1996), Eidvin et al. (1998b; paper 6), Eidvin and Nagy (1999; paper 7) and Channell et al. (1999).

Exploration drilling in the North Sea area since the early 1970s and in the Norwegian Sea continental shelf since the late 1970s has revealed thick deposits of late Cainozoic deposits also in these areas. This is especially the case for the northern margin of North Sea and the western margin of Norwegian Sea shelf where wedges similar to those of the Barents Sea margin are developed. However, these fans contain smaller volumes of sediments. It was assumed that the deposits were erosional products of an uplifted Fennoscandia, but the question arose how these were related in genesis and age to the deposits of the Barents Sea margin. The Mesozoic basins lying close to the coast were lifted together with Fennoscandia, and these might share the same problems as the Barents Sea shelf. Precise dating and correlation of the late Cainozoic succession along the entire Norwegian continental shelf became therefore of importance for the petroleum explorers.

Parts of the late Cainozoic sections recovered in the exploration wells have successively been dated by consultants commissioned by the oil companies. This work have not, in the same extent as in the western Barents Sea, met the problems of extensive reworking of microfossils, due to the fact that younger sedimentary rocks in lesser degree have been the source for these deposits. However, the Upper Cainozoic has usually not been given high priority by industrial research, and the datings are often inaccurate. Correlation of wells based on a variety of consultant-generated data can often be problematic, because of diverging taxonomic nomenclature and interpretations. These studies are often particularly inadequate with regard to the use of planktonic microfossils, and therefore correlate poorly with the deep sea record. The work at NPD with a detailed dating of the Upper Cainozoic deposits on the Senja Ridge (Eidvin et al., 1993; paper 5) was consequently extended to the entire Norwegian continental shelf, both southwards and northwards. This extended study was divided into several projects: Eidvin et al. (1999; paper 2) study the Late Oligocene to

Pleistocene of the central North Sea in two exploration and production wells from the Ekofisk and Sleipner fields. Eidvin and Rundberg (in press; paper 3) deals with the Oligocene to Pleistocene in eight exploration and production wells from the Tampen area (Snorre and Visund fields) and one well from the Troll field. This work emphasis the chronology of the early Neogene sands. Eidvin et al. (1998a; paper 4) is an investigation of the Oligocene to Pleistocene based on six exploration wells from the Utgard High, Halten Terrace and Nordland Ridge areas of the Norwegian Sea continental shelf. Eidvin et al. (1998b; paper 6) investigate the Middle Eocene to Pleistocene in well 7316/5-1 (Vestbakken Volcanic Province) in the western Barents Sea. Eidvin and Nagy (1999; paper 7) study the Upper Pliocene in ODP Hole 986D on the Svalbard Margin. Eidvin et al. (2000; paper 1) summarizes the findings of the other papers, and form a synthesis of the results.

In these studies, we employed several dating and correlation methods available including analyses of benthic and planktonic foraminifera, *Bolboforma*, radiolarians, dinoflagellates, diatoms, Sr-isotope dating and paleomagnetic polarity reversal chronology. Effort was made to apply the most efficient methods according to the stratigraphic level under investigation. However, most emphasis was placed on correlating planktonic foraminifera and *Bolboforma* assemblages with fossil zones from ODP and DSDP drillings in the Norwegian Sea and the North Atlantic, as these zones are paleomagnetically calibrated. As additional support to the correlation, lithological examination of the samples and petrophysical log correlation of the wells were executed. The wells were also tied together by regional 2D and 3D seismic lines.

In sum these studies have put the Cainozoic stratigraphy on a more consistent footing. We have developed a coherent stratigraphic scheme which is consistent for the entire margin from the central North Sea in the south to the Barents Sea in the north, and is also correlative to the deep sea record in the Norwegian Sea and North Atlantic. The studies have developed a new picture of rapid sedimentation, erosion and uplift in the late Cainozoic.

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Paper 1:
The Upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and North Atlantic

ELSEVIER

Marine and Petroleum Geology 17 (2000) 579–600

Marine and
Petroleum Geology

The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and the North Atlantic

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Received 6 September 1999; received in revised form 9 February 2000; accepted 14 February 2000

Abstract

A stratigraphic framework has been developed for the Cainozoic succession of the Norwegian continental shelf and margin. This framework is consistent for the entire margin from the central North Sea to the Barents Sea and also facilitates a correlation with the deep sea record of the Norwegian Sea and North Atlantic. A local system, mainly utilising planktonic and benthic foraminiferal assemblages and *Bolboforma* species, is developed. It can be potentially used for regional stratigraphic syntheses. Using this framework, a more precise and detailed identification and age assignments of Cainozoic, and in particular Neogene, strata can be performed. Several revisions of previous age assignments and a more detailed dating of the various sediment packages are presented. The most complete Neogene succession is recorded in the central North Sea. Further north the succession is interrupted by an increasing number of hiati of increasing duration. After a period of erosion in the late Middle to early Late Miocene there is a marked increase in the influx of terrigenous sediment in the Late Miocene. A period of transgression in the Early Pliocene resulted in strongly reduced rates of deposition, and sediments of this age are preserved mainly in the central North Sea. A period of regression in earliest Late Pliocene probably resulted in erosion of most of the Norwegian continental shelf with the exception of the deeper areas of the Central and Viking Grabens. This period was immediately followed in the later part of Late Pliocene, by rapid deposition of glacially derived sediment prograding along the entire shelf. In general, Pleistocene development is a continuation of the Late Pliocene evolution, but is marked by more extensive erosion of the inner shelf. This is inferred from the flat truncation of underlying prograding strata and the extensive build up of debris flow sediments within glacial fan depocentres. The entire Neogene development is closely related to the climatic evolution of high latitude regions surrounding the North Atlantic and the Norwegian-Greenland Sea.

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1. Introduction

The purpose of this paper is to present a stratigraphic framework for the Upper Cainozoic of the Norwegian continental shelf, and to document the distribution of Upper Cainozoic sediments along the entire shelf from the North Sea to Spitsbergen. The paper is a synthesis of several more detailed studies (Eidvin, Jansen & Riis, 1993; Eidvin, Brekke, Riis & Renshaw, 1998a; Eidvin, Goll, Grogan, Smelror & Ulleberg, 1998b; Eidvin, Riis & Rundberg, 1999; Eidvin & Nagy, 1999; Eidvin & Rundberg, in press). These studies, which are mainly biostratigraphic, but also include seismostratigraphic, lithostratigraphic, strontium isotope and paleomagnetic analyses, investigated petroleum wells and one ODP borehole in a transect from the central North Sea to the Svalbard Margin (Fig. 1). Their aims have been the dating of the Upper Cainozoic succession and main seismic

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PII: S0264-8172(00)00008-8

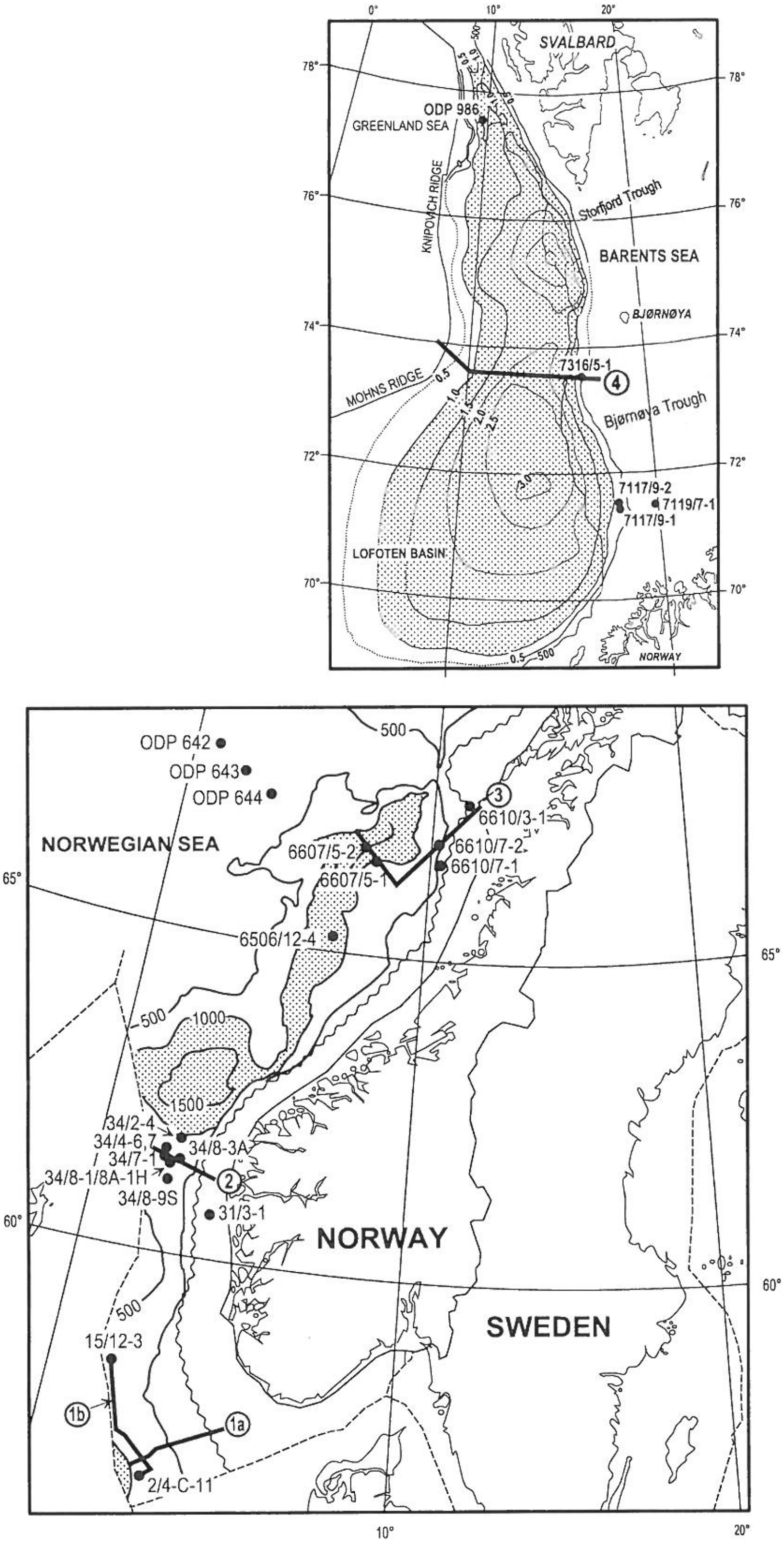

Fig. 1. Location of wells, ODP-boreholes and seismic lines studied. Thick lines show location of the regional profiles 1a-4 presented in Figs. 5–8. The ODP sites 642, 643 and 644 are used for correlation purposes. The map of the western Barents Sea and Svalbard Margin is an isopach map showing the thickness of glacial sediments in two-way travel time (s; modified after Faleide et al., 1996). The map of the North Sea and the Norwegian Sea continental shelf is an isopach map showing the thickness of Late Pliocene and Pleistocene sediments in two-way travel time (ms). The zig-zag line indicates the subcrop of the Upper Pliocene below the Pleistocene (modified after Riis, 1996).

boundaries in the various regions of the Norwegian shelf, and the interpretation of depositional environments based on microfaunal content. Precise dating is important in order to obtain a reliable correlation of the preserved Neogene succession along the shelf. Understanding of the Neogene geological development is necessary in order to construct basin models and to analyse the Late Cainozoic tectonism and glaciation of these areas.

The present paper emphasises the correlation of planktonic fossil assemblages from different regions of the shelf, and the correlation of shelf assemblages to fossil zones observed in the ODP and DSDP sites in the Norwegian Sea and North Atlantic. Most of the ODP and DSDP zonations are calibrated with nannoplankton zones and paleomagnetic chrons. The main emphasis is here placed on the age distribution of the Neogene deposits. Upper Palaeogene deposits are in most cases investigated in order to establish a lower boundary for the Neogene. The Neogene, and especially the Upper Pliocene which is most widely distributed, is the most thoroughly analysed and mapped. The following chapters are therefore presented starting with the youngest deposits and continuing back in time. In Eidvin et al. (1993, 1998a, 1998b, 1999) the time scale of Berggren, Kent and van Couvering (1985) was used, while in the present paper all absolute ages are converted to the time scale of Berggren, Kent, Swisher and Aubry (1995).

Since hydrocarbon exploration began in the North Sea in the 1960s many exploration and production wells have been drilled, and most areas along the Norwegian shelf have been explored. In most of these wells, routine biostratigraphic datings were carried out by contracted consultants. Traditionally, the Upper Cainozoic was not given high priority, and the datings are consequently often insufficient. Correlation of wells based on a variety of consultant-generated data can often be problematic, because of the differing taxonomic nomenclature and interpretations. Unpublished consultant reports are often particularly inadequate with regard to the use of planktonic foraminifera and *Bolboforma* (calcareous microfossils of uncertain origin). One reason for this is that recently revised zonations from ODP Leg 104 boreholes on the Vøring Plateau (Müller & Spiegler, 1993) were not considered in the interpretations. In addition, planktonic/benthic ratios are very low in deposits from some shelf areas. In this study, we overcame this problem by preparing and analysing larger sediment samples.

In addition to the papers by Eidvin and coworkers, several papers dating Upper Cainozoic deposits in hydrocarbon wells and cored shallow boreholes have been published in recent years: *North Sea*: Moe (1983), Gradstein, Kaminski and Berggren (1988), Rundberg and Smalley (1989), Knudsen and Asbjörndottir (1991), Siedenkrantz (1992), Gradstein, Kristiansen, Loemo and Kaminski (1992), Gradstein, Kaminski, Berggren, Kristiansen and D'Ioro (1994), Pedersen (1995), Sejrup, Aarseth, Ellingsen, Reither and Jansen (1987), Sejrup et al. (1995), Konradi (1996) and Laursen, Konradi and Bidstrup (1997); *Norwegian Sea continental shelf*: Haflidason, Aarseth, Haugen, Sejrup, Løvlie and Reither (1991) and Poole and Vorren (1993); *Barents Sea Margin*: Sættem, Poole, Ellingsen and Sejrup (1992), Sættem et al. (1994) and Mørk and Duncan (1993). However, in most of these, little attention was given to the analyses of planktonic fossils. Based on samples from numerous wells, King (1983, 1989) published a detailed foraminiferal zonation for the Cainozoic of the North Sea area. A detailed probabilistic zonation was also established by Gradstein and Bäckström (1996) for the North Sea and Haltenbanken areas. Stratlab (1988) published a broad biozonation of sediments from Triassic to Pleistocene age for the entire Norwegian Sea continental shelf.

Improved seismic mapping of the Cainozoic deposits of Norwegian Sea continental shelf reveals the need of improved age control of the major sequence boundaries. Papers important in this connection are listed below: *North Sea*: Rokoengen and Rønningsland (1983), Bjørslev Nielsen, Sørensen, Thiede and Skarbø (1986), Rundberg (1989), Cameron, Stoker and Long (1987), Cameron, Bulat and Mesdag (1993), Jensen and Schmidt (1992), Michelsen, Danielsen, Heilmann-Clausen, Jordt, Laursen and Thomson (1994), Sørensen and Michelsen (1995), Jordt, Faleide, Bjørlykke and Ibrahim (1995), King, Sejrup, Haflidason, Elverhøi and Aarseth (1996), Sejrup, King, Aarseth, Haflidason and Elverhøi (1996), Sørensen, Gregersen, Breiner and Michelsen (1997), Danielsen, Michelse and Rønø Clausen (1997), Veeken (1997), Gregersen, Michelsen and Sørensen (1997), Gregersen (1998), Michelsen, Thomsen, Danielsen, Helmann-Clausen, Jordt and Laursen (1998), Martinsen, Bøen, Charnock, Mangerud and Nøttvedt (1999), Clausen, Gregersen, Michelsen and Sørensen (1999) and Jordt, Faleide, Thyberg and Bjørlykke (in press); *Norwegian Sea continental shelf*: Rokoengen et al. (1995), Sættem, Riise, Rokoengen and By (1996), Henriksen and Vorren (1996), Henriksen and Weimer (1996) and Swiecicki, Gibbs, Farrow and Coward (1998); *Barents Sea and Svalbard Margin*: Spencer, Home and Berglund (1984), Nøttvedt, Berglund, Rasmussen and Steel (1988), Vorren, Lebesbye, Andreassen and Larsen, (1989), Vorren, Richardsen, Knutsen and Henriksen (1990, 1991), Richardsen, Knutsen, Vail and Vorren (1993), Knutsen et al. (1993), Faleide, Solheim, Fiedler, Hjelstuen, Andersen and Vanneste (1996), Fiedler and Faleide

(1996), Hjelstuen, Elverhøi and Faleide (1996) and Solheim, Andersen, Elverhøi and Fiedler (1996).

2. Geological setting

Exploration wells and boreholes located on a transect from the central North Sea to the Svalbard Margin are situated in many different structural settings. Wells 2/4-C-11, 15/12-3, 31/3-1, 34/8-9S, 34/8A-1H, 34/8-1, 34/8-3A, 34/7-1, 34/4-7, 34/4-6 and 34/2-4 are all located in the North Sea Basin (Fig. 1). The North Sea Basin is epicontinental, confined by the Scandinavian and British landmases, with a marine connection in the north to the Norwegian-Greenland Sea. The basin comprises several major Mesozoic highs and grabens of which the Central Graben in its south-central region, and the Viking Graben in the north are dominant. These structures were formed during several periods of extensional tectonism during the Permian and the Mesozoic. This extension ceased in the Cretaceous and the basin was subjected to post-rift subsidence and filled by sediments derived from surrounding topographical highs (Gregersen et al., 1997).

Well 2/4-C-11 is situated in the Central Graben, well 15/12-3 in the southern Viking Graben, well 31/3-1 on the Horda Platform, wells 34/8-9S, 34/8A-1H, 34/8-1, 34/8-3A, 34/7-1, 34/4-7 and 34/4-6 on the Tampen Spur High and well 34/2-4 on the northernmost Tampen Spur.

Wells from the Norwegian Sea continental shelf are situated in two different structural settings (Fig. 1). Wells 6607/5-1, 6607/5-2 and 6506/12-4 are located in the Vøring Basin, which is characterised by an exceptionally thick Cretaceous succession and a complex Cretaceous and Tertiary tectonic history (Blystad, Brekke, Færseth, Larsen, Skogseid & Tørudbakken 1995; Brekke, in press). Wells 6607/5-1 and 6607/5-2 are situated on the Utgard High which forms the eastern flank of the Late Cretaceous Någrind Syncline. The wells reveal a complex and condensed Palaeogene and a very thick post-Cenomanian Cretaceous succession. Wells 6610/3-1, 6610/7-2 and 6610/7-1 are located on the tectonically more stable Late Jurassic/Early Cretaceous Trøndelag Platform (Blystad et al., 1995; Brekke, in press). The succession is here characterised by a condensed Cretaceous sequence and, in places, a deeply eroded Tertiary succession (Eidvin et al., 1998a).

Wells 7117/9-1, 7117/9-2, 7119/7-1, 7316/5-1 and the ODP borehole 986D are situated on the Barents Sea and Svalbard Margins (Fig. 1). The evolution of this margin is closely linked to the gradual northward opening of the Norwegian-Greenland Sea. The margin consists of three main structural segments: (1) a southern sheared margin along the Senja Fracture Zone (70–72°30′ N) where the wells 7117/9-1, 7117/9-2 and 7119/7-1 are located, (2) a central rift complex associated with volcanism (72°30′–75° N) where well 7316/5-1 is situated, and (3) a northern initially sheared, and later rifted, margin along the Hornsund Fault Zone (75–80° N) where the ODP Borehole 986D is located (Faleide, Gudlaugsson, Eldholm, Myhre & Jackson 1991; Faleide, Vågnes & Gudlaugsson 1993; Faleide et al., 1996).

3. Material and analyses

This study is based on the investigation of approximately 1120 samples from 22 wells and boreholes (Fig. 1). The biostratigraphic analyses are based largely on ditch cutting samples. Ditch cuttings are usually taken at 10 m in those parts of the wells which are outside the reservoir intervals. In some cases the sampling interval is 3–5 m. Normally all the available samples were analysed, except some thick intervals which were analysed at 20 m segments. Short conventional cores were available for some wells; 2/4-C-11 (six cores: approximately 1.3, 8.4, 5.5, 6.3, 15.0, 8.2 m), 34/8A-1H (one core: approximately 12.0 m), 34/8-9S (one core: approximately 4.8 m) and 7316/5-1 (three cores: approximately 10.6, 26.9, 11.5 m). ODP borehole 986D was cored continuously. Sidewall cores were available in wells 2/4-C-11 (49 cores), 34/4-7 (12 cores), 34/7-1 (14 cores), 6610/3-1 (five cores), 6610/7-2 (seven cores) and 7316/5-1 (34 cores).

During normal exploration operations, the sampling of ditch cuttings does not usually commence before the well has reached a depth between 100 and 300 m below the sea floor. Consequently, the upper part of the wells can not usually be analysed, but in some wells sidewall cores are available. In some wells in areas with very thick Upper Pliocene section, and where this part was thoroughly investigated, the analysis started in the lower part of the Upper Pliocene.

The biostratigraphic investigations are based primarily on planktonic and benthic foraminifera. In addition, the Middle to Upper Miocene sections were also analysed for *Bolboforma*. The Upper Oligocene to Lower Miocene and the Upper Palaeocene to Lower Eocene sections were analysed for diatoms and the Lower/Middle Eocene sections for radiolarians. The Lower Oligocene sections in wells 6610/7-1 and 6610/3-1 were also analysed for dinoflagellates. In well 7316/5-1 the entire investigated column was analysed for both dinoflagellates and radiolarians in addition to foraminifera, but only the foraminiferal assemblages are listed in the present paper.

Strontium isotope analyses were performed on the entire section, or portions of sections in the wells 2/4-

C-11, 31/3-1, 34/2-4, 34/4-6, 34/4-7, 34/7-1, 34/8-1, 34/8A-1H, 34/8-9S, 6610/3-1, 7117/9-1, 7117/9-2, 7316/5-1 and ODP borehole 986D. In most cases, the tests of calcareous foraminifera and *Bolboforma* were analysed for strontium isotopes, but molluscs and *Bryozoa* fragments were also used in some wells. The analysed material was taken mainly from sidewall cores and conventional cores, but ditch cutting samples were also used. Ages for these samples were obtained by comparing the measured $^{87}Sr/^{86}Sr$-ratio to the global strontium isotope curves of Farrell, Clemens and Gromet (1995) and Howarth and McArthur (1997).

The lithologic analyses were based on the visual examination of the samples both prior to treatment, and of the dispersed and fractionated material after preparation. Petrophysical logs were also employed in the descriptions.

Paleomagnetic analyses were performed on two conventional cores in the Pleistocene in well 2/4-C-11.

Descriptions of methods of fossil preparation, range charts of the stratigraphically important fossils, results of strontium isotope analyses, detailed lithological descriptions and definitions of lithostratigraphic units are reported in Eidvin et al. (1993, 1998a, 1998b, 1999), Eidvin and Nagy (1999) and Eidvin and Rundberg (in press). Lithostratigraphic units are shown in Fig. 3(a) and (b) in the present paper, but are not discussed. The lithostratigraphic nomenclatures are after Isaksen and Tonstad (1989) for the North Sea and Dalland, Wosley and Ofstad (1988) for the Norwegian Sea continental shelf and the Barents Sea.

4. Biostratigraphic correlation

The standard Cainozoic zonal scheme is based on planktonic foraminiferal and calcareous nannoplankton distributions established in tropical and sub-tropical areas. In middle and high latitudes, the assemblages become progressively less diverse and many key species are lacking (King, 1983). High-latitude planktonic foraminiferal associations are characteristically low diversity faunas composed of long-ranging species. Consequently, it is not generally possible to apply the standard zonations established for low latitudes (Blow, 1969, 1979; Bolli & Saunders, 1985), or for northern temperate regions (Berggren, 1972; Poore & Berggren, 1975; Poore, 1979; Weaver & Clement, 1986) to high-latitude regions. Studies of ODP Leg 104 sites on the Vøring Plateau in the Norwegian Sea and ODP/DSDP-boreholes in the North Atlantic resulted in local high-latitude Neogene planktonic foraminiferal and *Bolboforma* zonations (Spiegler & Jansen, 1989; Quale & Spiegler, 1989; Spiegler & Müller, 1992; Müller & Spiegler, 1993). Most of these zones are calibrated with nannoplankton and paleomagnetic data. Comparing these zonations with planktonic fossil assemblages from Norwegian shelf deposits has proven useful for dating and correlation along the entire Norwegian shelf.

Calcareous fossils are mostly dissolved in sediments older than the late Middle Miocene in ODP/DSDP boreholes on the Vøring Plateau (Henrich, 1989; Spiegler & Jansen, 1989; Müller & Spiegler, 1993). However, planktonic foraminifera from the early Middle and Early Miocene are known from the North Atlantic (DSDP Leg 49; Poore, 1979) and the North Sea (King, 1989; Gradstein & Bäckström, 1996).

In some sections planktonic foraminifera are rare due to nearshore environments of deposition or post-mortem dissolution. Benthic foraminifera are therefore also important for dating Cenozoic shelf sediments. However, correlation of benthic foraminifera over long distances is not always reliable due to variation in assemblage composition resulting from environmental factors.

The correlation of benthic foraminifera is generally in accordance with the zonations of King (1983, 1989) from the North Sea, Gradstein and Bäckström (1996) from the North Sea and Haltenbanken, and Stratlab (1988) from the Norwegian Sea continental shelf.

Detailed presentation and discussion of the fossil data in the investigated wells are found in Eidvin et al. (1993, 1998a, 1998b, 1999), Eidvin and Nagy (1999) and Eidvin and Rundberg (in press). The assemblages discussed in the above papers are only listed in the present paper (Tables 1–6; Figs. 2 and 3(a)–(b)). The general planktonic fossil correlation between deep sea and shelf deposits is however explained in the following. In Eidvin et al. (1993, 1998a, 1998b) the downhole fossil distribution patterns are classified as biozones. The biozones were, however, defined by criteria that are better described as 'assemblages'. The term 'assemblages' therefore replaces 'biozones' in the present paper.

5. Results

5.1. Pleistocene

5.1.1. Microfossil assemblages

Pleistocene sediments are observed in central North Sea wells 2/4-C-11 (Ekofisk Field) and 15/12-3 (Sleipner area; Fig. 1). In well 2/4-C-11 the Pleistocene corresponds to the benthic foraminiferal assemblages CE-AB, CE-BB, CE-CB and the planktonic foraminiferal assemblage CE-AP (Table 1; Figs. 2 and 3(a)). In well 15/12-3 the Pleistocene corresponds to the benthic foraminiferal assemblages CS-AB, CS-BB and the upper part of CS-CB (Table 2, Figs. 2 and 3(a)).

Of the nine wells from the northern North Sea, Pleistocene sediments are sampled only in well 31/3-1 (Troll Field) where these deposits correspond to the foraminiferal assemblage N-A (Table 3; Figs. 1–3(a)).

In the Norwegian Sea continental shelf Pleistocene sediments are observed in wells 6506/12-4 (Halten Terrace), 6607/5-1 (Utgard High) and 6610/7-2 (Nordland Ridge; Fig. 1) and correspond to the foraminiferal assemblage M-A (Table 4; Figs. 2 and 3(b)).

In the western Barents Sea continental margin Pleistocene deposits are recorded in wells 7117/9-1, 7117/9-2 and 7119/7-1 (Senja Ridge) and 7316/5-1 (Bjørnøya West area; Fig. 1). In wells 7117/9-1, 7117/9-2 and 7119/7-1 the Pleistocene corresponds to foraminiferal assemblage BS-A (Table 5; Figs. 2 and 3(b)). In well 7316/5-1 the Pleistocene corresponds to the foraminiferal assemblage BB-FA and probably the upper part of Unzoned Interval f1 (Table 6; Figs. 2 and 3(b)).

5.1.2. Correlation with the deep sea record

The planktonic foraminiferal faunas in all the wells mentioned above can be correlated with the assemblages in the ODP/DSDP deep sea boreholes where a *N. pachyderma* (sinistral) zone is described by Weaver and Clement (1986) from the North Atlantic and by Spiegler and Jansen (1989) from the Vøring Plateau in sediments younger than 1.8 Ma (Fig. 4). At the open ocean sites, an encrusted variety of the sinistrally coiled *N. pachyderma* dominates over an unencrusted form. The encrusted variety occurs only very sporadically in older sediments, while the unencrusted one occurs also in Pliocene deposits. Except for the wells 2/4-C-11 and 15/12-3, *N. pachyderma* (sinistral; encrusted) is recorded from all the analysed sections. In well 2/4-C-11 and 15/12-3 only a few *N. pachyderma* (sinistral, unencrusted) are recorded. The reason for this is probably that the specimens observed in these intervals are small juvenile forms, and that the larger encrusted forms have not reached the shallow marine environment that prevailed at these sites.

5.1.3. Regional synthesis

Over large areas of the Norwegian continental shelf a hiatus is recorded between the Upper Pliocene and the Pleistocene. In most areas, this hiatus is observed on seismic sections as a distinct reflector. Flat-lying Pleistocene beds lie with an angular unconformity on more or less progradational Upper Pliocene deposits. Older Tertiary and Mesozoic strata are tilted, dip towards the west, and are truncated towards the coast (Sigmond, 1992). The seismic reflector between the Pleistocene and the Upper Pliocene becomes less dis-

Table 1
Planktonic and benthic faunal assemblages with index fossils and ages in well 2/4-C-11 from the central North Sea, based on Eidvin et al. (1999)

Designation[a]	Assemblage	Series/subseries
Planktonic fossil assemblages		
CE-AP	*Neogloboquadrina pachyderma* (sin.)	Upper Pliocene–Pleistocene
CE-BP	*Neogloboquadrina pachyderma* (dex.)	Upper Pliocene
CE-CP	*Globigerina bulloides*	Upper Pliocene
CE-DP	*Globigerina bulloides-Neogloboquadrina atlantica* (sin.)	Lower–Upper Pliocene
CE-EP	Lower *Neogloboquadrina atlantica* (dex.)	Upper Miocene
CE-FP	*Neogloboquadrina acostaensis*	Upper Miocene
CE-GP	*Bolboforma metzmacheri*	Upper Miocene
CE-HP	*Bolboforma fragori-Bolboforma subfragori*	Middle–Upper Miocene
CE-IP	*Globigerina praebulloides-Globigerinoides quadrilobatus triloba*	Middle Miocene
CE-JP	*Globigerina ciperoensis*	Lower Miocene
CE-KP	Diatom sp. 4	Lower Miocene
CE-LP	Diatom sp. 3	Upper Oligocene
Benthic fossil assemblages		
CE-AB	*Elphidium excavatum*	Pleistocene
CE-BB	*Elphidium excavatum-Haynesina orbiculare*	Pleistocene
CE-CB	*Elphidium excavatum-Cassidulina teretis*	Pleistocene
CE-DB	*Cibicides grossus*	Upper Pliocene
CE-EB	*Monspliensina pseudotepida*	Upper-Pliocene
CE-FB	*Cibicidoides limbatosuturalis*	Lower–Upper Pliocene
CE-GB	*Uvigerina venusta saxonica*	Upper Miocene–Lower Pliocene
CE-HB	*Glomospira charoides*	Middle–Upper Miocene
CE-IB	*Bulimina elongata*	Middle Miocene
CE-JB	*Uvigerina tenuipustulata*	Lower Miocene
CE-KB	*Ammodiscus sp. A-Cyclammina placenta*	Lower Miocene
CE-LB	*Spirosigmoilinella compressa*	Lower Miocene
CE-MB	*Annectina biedai*	Upper Oligocene–Lower Mioc.

[a] Abbreviation of the assemblage designation: C = Central North Sea, E = Ekofisk Field, B = Benthic and P = Planktonic.

Table 2
Planktonic and benthic faunal assemblages with index fossils and ages in well 15/12-3 from the central North Sea, based on Eidvin et al. (1999)

Designation[a]	Assemblage	Series/subseries
Planktonic fossil assemblages		
CS-AP	*Neogloboquadrina pachyderma* (dex.)	Upper Pliocene
CS-BP	*Upper Neogloboquadrina* atlantica (dex.)	Upper Pliocene
CS-CP	*Globigerina bulloides*	Upper Pliocene
CS-DP	*Globigerina bulloides-Neogloboquadrina atlantica* (sin.)	Lower–Upper Pliocene
CS-EP	*Neogloboquadrina atlantica* (dex.)-*N. acostaensis*	Upper Miocene
CS-FP	*Boldoforma fragori-Bolboforma subfragori*	Middle–Upper Miocene
CS-GP	*Bolboforma badenensis-Bolboforma reticulata*	Middle Miocene
CS-HP	*Globigerina praebulloides*	Middle Miocene
CS-IP	*Globigerina ciperoensis-Globigerina woodi*	Lower Miocene
CS-JP	Diatom sp.4	Lower Miocene
CS-KP	Diatom sp.3	Upper Oligocene
Benthic fossil assemblages		
CS-AB	*Elphidium excavatum-Haynesina orbiculare*	Pleistocene
CS-BB	*Elphidium excavatum-Cassidulina teretis*	Pleistocene
CS-CB	*Cibicides grossus*	Upper Pliocene-Pleistocene
CS-DB	*Monspeliensina pseudotepida*	Upper Pliocene
CS-EB	*Cibicidoides limbatosuturalis-Unigerina venusta saxonica*	Upper Miocene–Lower Pliocene
CS-FB	*Uvigerina pygmea langenfeldensis*	Middle-Upper Miocene
CS-GB	*Uvigerina* sp. A	Middle Miocene
CS-HB	*Asterigerina guerichi staeschei*	Middle Miocene
CS-IB	*Uvigerina tenuipustulata*	Lower Miocene
CS-JB	*Plectofrondicularia seminuda*	Lower Miocene
CS-KB	*Bolivina antiqua*	Lower Miocene
CS-LB	*Cibicides sulzensis*	Upper Oligocene-Lower Mioc

[a] Abbreviation of the assemblage designation are as follows: C = Central North Sea, S = Sleipner Field, B = Benthic and P = Planktonic.

tinct towards both the central North Sea and towards the continental shelf break in areas further north.

This reflector was investigated in a cored geotechnical borehole from the Troll Field (close to well 31/3-1). These cores have been subjected to among other paleomagnetic analyses, and the base of the Pleistocene section is dated to 1.2 Ma (Sejrup et al., 1995). This dating coincides with a marked intensification of glacial activity as is observed in the deep sea record (Prell, 1982; Ruddiman, Raymo & McIntyre, 1986; Berger & Jansen, 1994). Erosion between the Upper Pliocene and Pleistocene was probably caused either by the advance of the glacial front or by a glacio-isostatic drop in sea-level. The lower part of the Pleistocene and uppermost part of the Upper Pliocene are eroded over large areas of the continental shelf.

Table 3
Faunal assemblages with index fossils and ages in wells 31/3-1, 34/8-9S, 34/8A-1H, 34/8-1, 34/8-3A, 34/7-1, 34/4-7, 34/4-6 and 34/2-4 from the northern North Sea, based on Eidvin and Rundberg (in press)

Designation[a]	Assemblage	Series/subseries
N-A	*Nonion labradoricum-Neogloboquadrina pachyderma* (sin.)	Pleistocene
N-B1	*Cibicides grossus-Elphidiella hannai-Globigerina bulloides-Neogloboquadrina atlantica* (sin.)	Upper Pliocene
N-B2	*Cibicides grossus-Elphidium albiumbilicatum-Globigerina bulloides-Neogloboquadrina atlantica* (sin.)	Upper Pliocene
N-C1	*Ehrenbergina variabilis*	Upper Miocene–Lower Pliocene
N-C2	*Cibicides dutemplei*	Upper Miocene–Lower Pliocene
N-D	*Eponides umbonatus-Stilostomella* sp.-Diatom sp.	Lower Miocene
N-E	Diatom sp.4–Diatom sp.5	Lower Miocene
N-F1	*Turrilina alsatica*-Diatom sp.3	Lower–Upper Oligocene
N-F2	*Turrilina alsatica*	Lower–Upper Oligocene
N-F3	*Gyroidina soldanii girardana*	Lower–Upper Oligocene
N-F4	Diatom sp.3	Lower–Upper Oligocene
N-G	*Turrilina alsatica-Gyroidina soldanii mamillata-Stilostomella hirsuta*	Lower Oligocene

[a] Abbreviation of assemblage designation: N = northern North Sea.

Table 4
Faunal assemblages with index fossils and ages in wells 6506/12-4, 6607/5-1, 6607/5-2, 6610/7-2, 6610/7-1 and 6610/3-1 from the Norwegian Sea continental shelf based on Eidvin et al. (1998a)

Designation[a]	Assemblage	Series/subseries
M-A	*Neogloboquadrina pachyderma* (sin.)-*Nonion labradoricum*	Pleistocene
M-B	*Cibicides grossus*	Upper Pliocene
M-C	*Cibicides grossus-Globigerina bulloides-Neogloboquadrina atlantica* (sin.)	Upper Pliocene
M-D	*Cibicides grossus-Elphidiella hannai-Globigerina bulloides-Neogloboquadrina atlantica* (sin.)	Upper Pliocene
M-E	*Cibicides grossus-Elphidiella hannai*	Upper Pliocene
M-F	*Elphhidiella hannai*	Upper Pliocene
M-G	*Nonion affine-Neogloboquadrina atlantica* (dex.)	Upper Miocene
M-H	*Cibicides telegdi-Eponides pygmeus-Neogloboquadrina atlantica* (dex.)	Upper Miocene
M-I	*Ehrenbergina variabilis-Globocassidulina subglobosa-Neogloboquadrina atlantica* (dex.)	Upper Miocene
M-J	*Bolboforma metzmacheri*	Upper Miocene
M-K	*Bolboforma subfragori-Bolboforma fragori*	Middle–Upper Miocene
M-L	Diatom sp. 3	Upper Oligocene–Lower Mioc.
M-M	*Gyroidina soldanii girardana-Bolivina* cf. *antiqua*	Lower Oligocene
M-N	*Cenosphaera* sp.	Lower–Middle Eocene
M-O	*Coscinodiscus* sp. 1	Upper Palaeocene–Lower Eocene

[a] M = Mid-Norway.

Table 5
Faunal assemblages with index fossils and ages in wells 7117/9-2, 7117/ 9-1 and 7119/7-1 from the Senja Ridge on western Barents Sea margin, based on Eidvin et al. (1993)

Designation[a]	Assemblage	Series/subseries
BS-A	*Neogloboquarina pachyderma* (sin.)-*Islandiella islandica*	Pleistocene
BS-B	*Cibicides grossus*	Upper Pliocene
BS-C	*Elphidiella hannai*	Upper Pliocene
BS-D	Geodia sp.-*Globigerina bulloides*	Upper Pliocene

[a] B = Barents Sea, S = Senja Ridge.

5.2. Upper Pliocene

5.2.1. Microfossil assemblages

Upper Pliocene deposits are recorded in the central North Sea wells 2/4-C-11 (Ekofisk Field) and 15/12-3 (Sleipner area; Fig. 1). In well 2/4-C-11 these deposits correspond to the benthic foraminiferal assemblages CE-DB, CE-EB and upper part of CE-FB. Planktonic foraminiferal assemblages include CE-BP, CE-CP and the upper part of CE-DP (Table 1; Figs. 2 and 3(a)). In well 15/12-3 the Upper Pliocene corresponds to the benthic assemblages CS-CB (lower part) and CS-DB. Planktonic foraminiferal assemblages include CS-BP, CS-CP and the upper part of CS-EP (Table 2; Figs. 2 and 3(a)).

In the northern North Sea Upper Pliocene sediments are recorded in wells 34/4-6, 34/4-7, 34/7-1 (Snorre Field), 34/8-1, 34/8A-1H, 34/8-3A and 34/8-9S (Visund Field) and 34/2-4 corresponding to the foraminiferal

Table 6
Faunal assemblages with index fossils and ages in well 7316/5-1 from the Bjørnøya West area on the western Barents Sea margin, based on Eidvin et al. (1998b)

Designation[a]	Assemblage	Series/subseries
BB-FA	*Neogloboquadrina pachyderma* (sin.)-*Elphidium excavatum-Cassidulina reniforme*	Pleistocene
BB-FB	*Globigerina bulloides-Cassidulina teretis*	Upper Pliocene
BB-FC	*Cyclammina placenta*	Upper Oligocene–Lower Mioc.
BB-FD	*Turrilina alsatice-Angulogerina tenuistriata*	Lower Oligocene
BB-FE	*Cibicides proprius-Spiroplectammina navarroana-Pseudohastigerina micra-Pseudohastigerina* sp.	Middle Eocene
BB-FF	*Cibicides propius-Vaginulinopsis decorata-Spiroplectammina navarroana-Pseudohastigerina micra*	Middle Eocene
BB-FG	*Spiroplectammina navarroana-Spiroplectammina carinata*	Middle Eocene

[a] B = Barents Sea, B = Bjørnøya West.

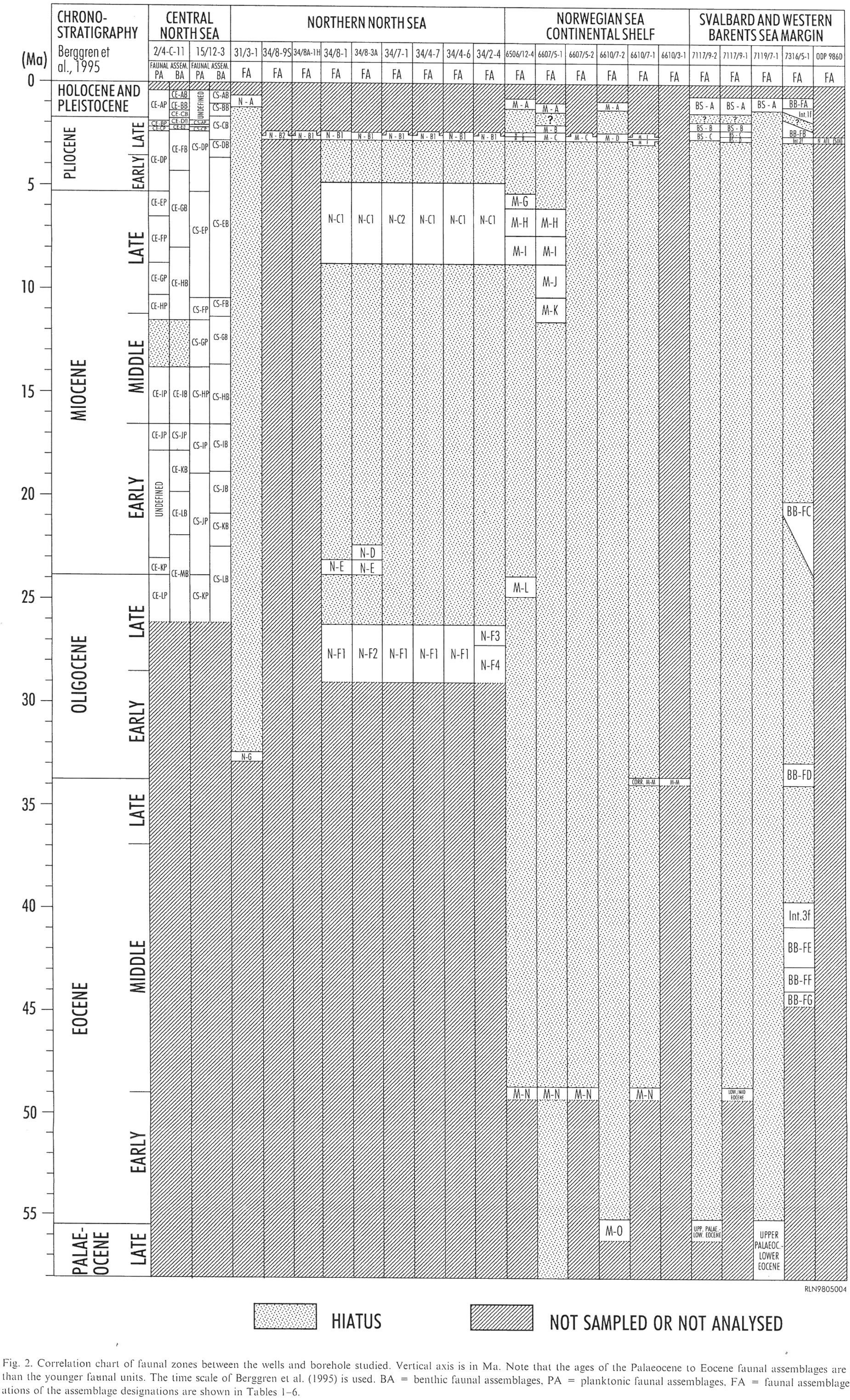

Fig. 2. Correlation chart of faunal zones between the wells and borehole studied. Vertical axis is in Ma. Note that the ages of the Palaeocene to Eocene faunal assemblages are less precise than the younger faunal units. The time scale of Berggren et al. (1995) is used. BA = benthic faunal assemblages, PA = planktonic faunal assemblages, FA = faunal assemblages. Abbreviations of the assemblage designations are shown in Tables 1–6.

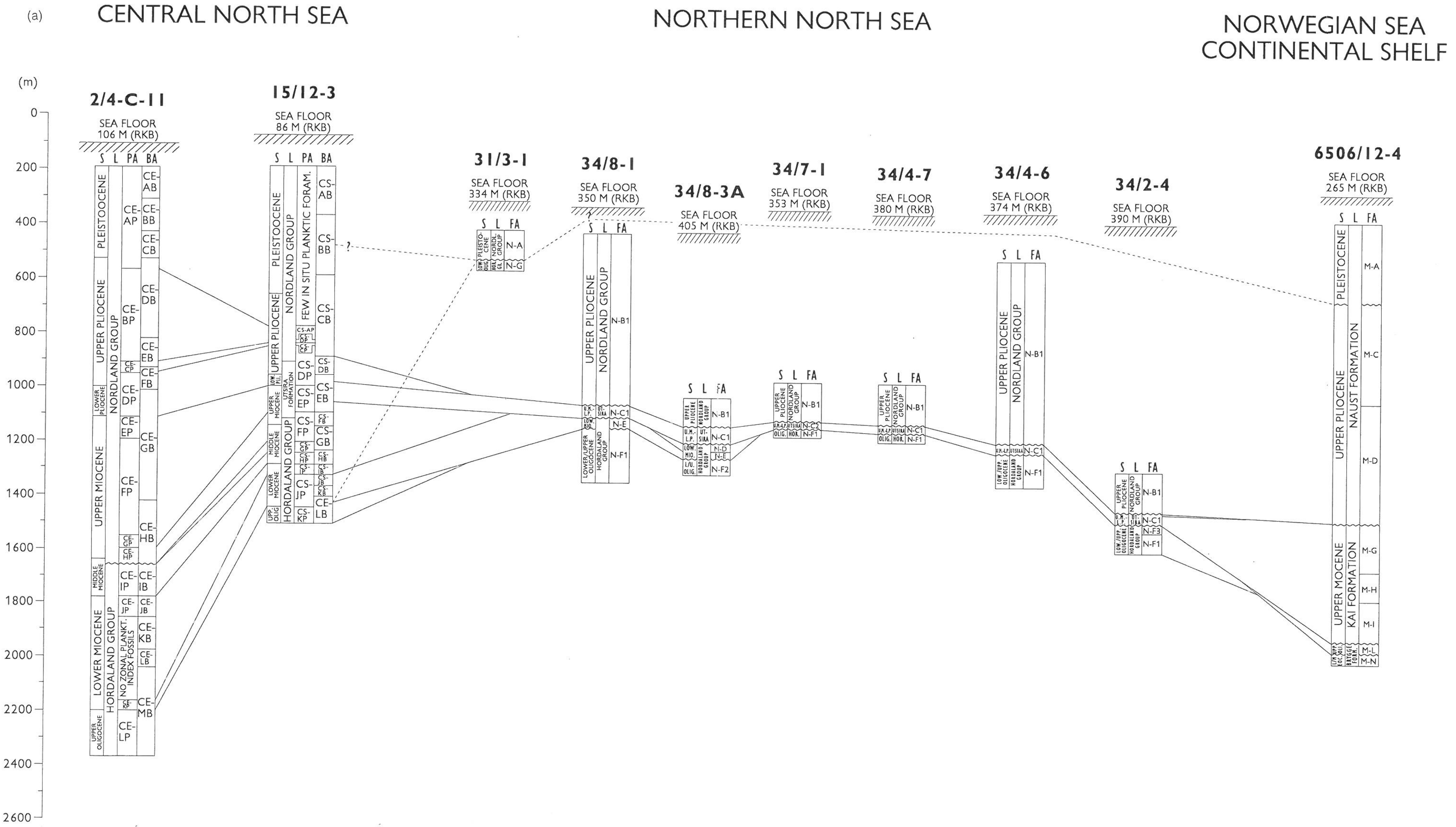

Fig. 3. (a) Correlation of the faunal assemblages between the wells studied from the central and northern North Sea, and from well 6506/12-4 from the Norwegian Sea continental shelf. Vertical axis is in metre below rig floor. S = series/subseries, L = lithostratigraphic units, BA = benthic faunal assemblages, PA = planktonic faunal assemblages, FA = faunal assemblages, m RKB = metre below rig floor, UM-LP = Upper Miocene to Lower Pliocene. Abbreviations of the assemblage designations are shown in Tables 1–6. The investigated core sections of the wells 34/8A-1H and 34/8-9S are too short to be included in this figure. (b) Correlation of the faunal assemblages between wells and borehole studied from the Norwegian Sea continental shelf, western Barents Sea and Svalbard Margin. L/M Eoc. = Lower/Middle Eocene, Nau. For. = Naust Formation, Bry. Form. = Brygge Formation.

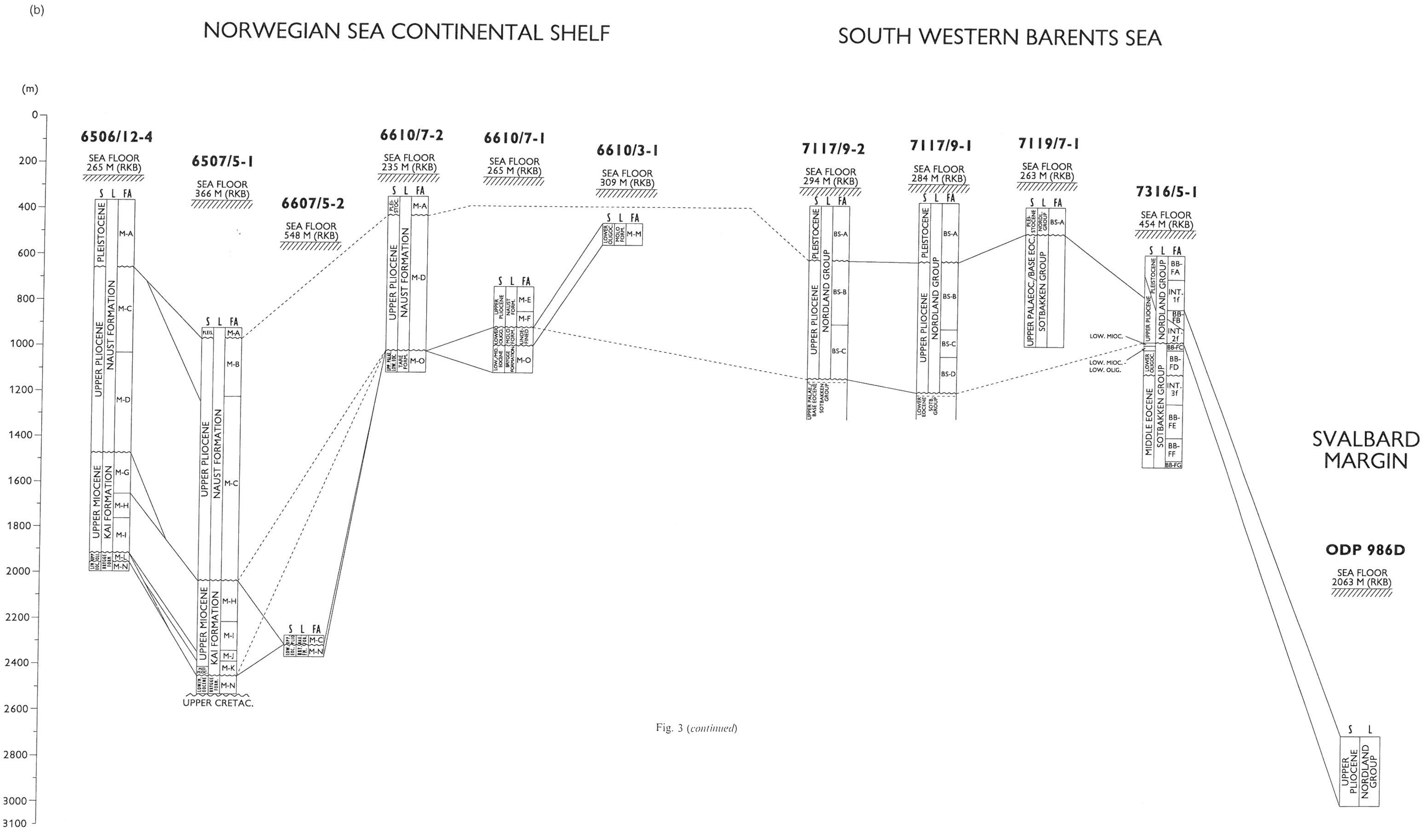

Fig. 3 (*continued*)

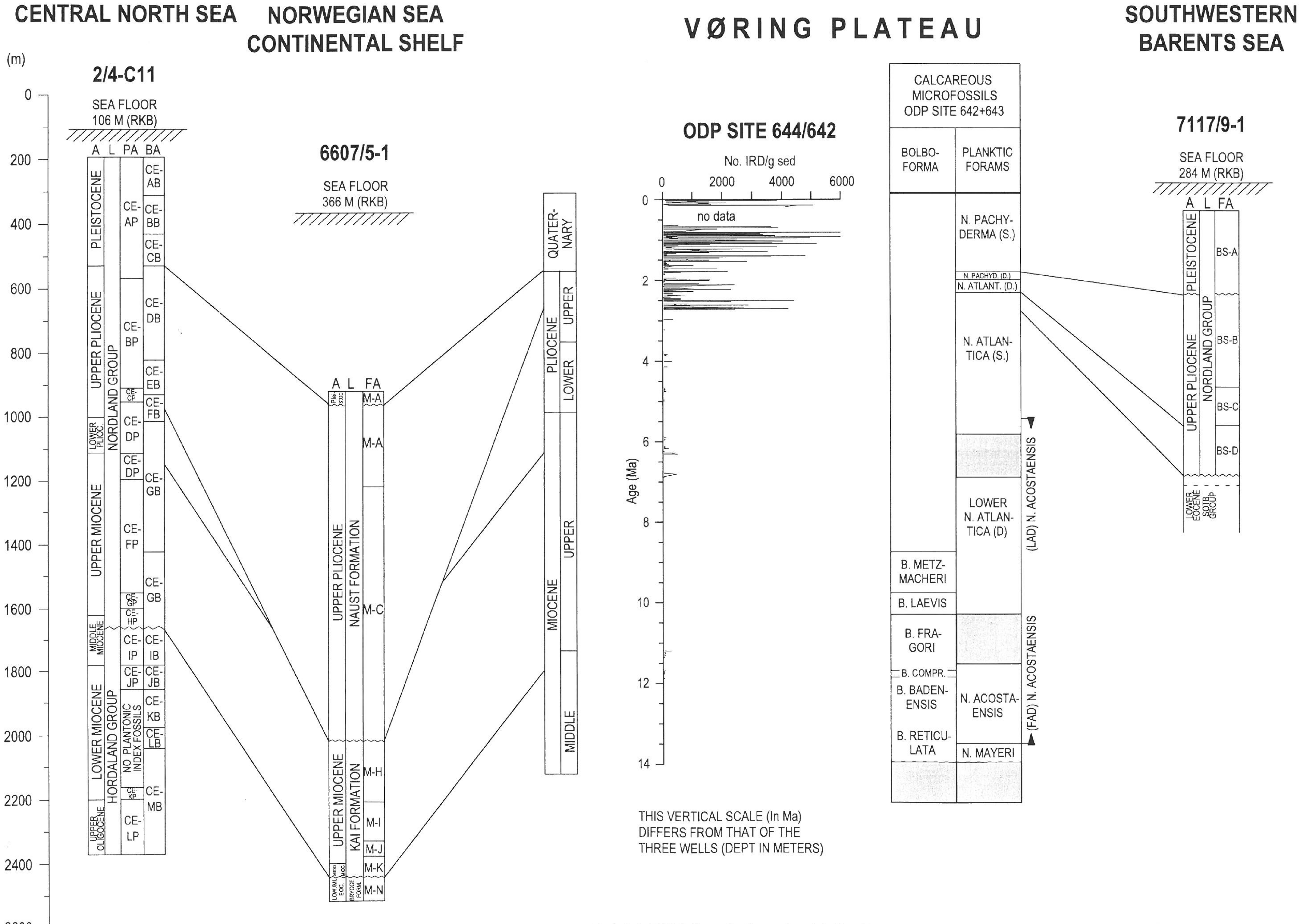

Fig. 4. Correlation of the Vøring Plateau ODP Leg 104 sites and the stratigraphy of the wells 2/4-C-11 (central North Sea), 6607/5-1 (Norwegian Sea continental shelf) and 7117/9-1 (southwestern Barents Sea). The IRD (ice rafted detritus) curve is after Jansen and Sjøholm (1991) and Frondval and Jansen (1996). The fossil zones of ODP Leg 104 sites are after Spiegler and Jansen (1991) and Müller and Spiegler (1993). S = series/subseries, L = lithostratigraphic units, BA = benthic faunal assemblages, PA = planktonic faunal assemblages, FA = faunal assemblages, m RKB = metre below rig floor. Abbreviations of the assemblage designations are shown in Tables 1–6.

assemblages N-B1, and in well 34/8-9S to N-B2 (Table 3; Figs. 1–3(a)).

In the Norwegian Sea continental shelf Upper Pliocene sediments are found in wells 6506/12-4 (Halten Terrace), 6607/5-1, 6607/5-2 (Utgard High), 6610/7-1 and 6610/7-2 (Nordland Ridge; Fig. 1). In well 6506/12-4 these sediments correspond to the foraminiferal assemblages M-C and M-D, in well 6607/5-1 to M-B and M-C, in well 6607/5-2 to M-C, in well 6610/7-1 to M-E and M-F and in well 6610/7-2 to M-D (Table 4; Figs. 2 and 3(b)).

In the western Barents Sea continental margin Upper Pliocene deposits are recorded in wells 7117/9-1, 7117/9-2 (Senja Ridge), 7316/5-1 (Bjørnøya West area) and the borehole ODP 986D (Svalbard Margin; Fig. 1). In well 7117/9-1 and 7117/9-2 the Upper Pliocene corresponds to foraminiferal assemblages BS-B, BS-C and in well 7117/9-1 also to BS-D (Table 5; Figs. 2 and 3(b)). In well 7316/5-1 the Upper Pliocene corresponds to the lower part of Unzoned Interval f1, assemblage BB-FB and Unzoned Interval f2 (Table 6; Figs. 2 and 3(b)). In ODP 986D the Upper Pliocene corresponds to the benthic *Melonis zaandamae–C. teretis* Assemblage and the planktonic *N. atlantica* (sinistral) Assemblage (Figs. 2 and 3(b)).

5.2.2. Correlation with the deep sea record

In ODP/DSDP deep sea boreholes on the Vøring Plateau the planktonic foraminiferal fauna is characterised by the *N. atlantica* (sinistral) Zone and the upper *N. atlantica* (dextral) Zone of Spiegler and Jansen (1989). The *N. atlantica* (sinistral) Zone spans the Pliocene to latest Miocene in age (Fig. 4). This zone is also rich in *G. bulloides*. On the Vøring Plateau the LO (last occurrence) of *N. atlantica* (sinistral) is no younger than 2.4 Ma (Spiegler & Jansen, 1989). Throughout the last 2.4 Ma *G. bulloides* is only rarely found in the warmest interglacials of the last 1 Ma (Spiegler & Jansen, 1989; Kellogg, 1977). The LO of *N. atlantica* (dextral) is close to the Pleistocene/Pliocene boundary. This species also occurs sporadically in the *N. atlantica* (sinistral) Zone of Spiegler and Jansen (1989).

In most wells studied, the planktonic foraminiferal assemblages consist mainly of *N. atlantica* (sinistral) and *G. bulloides* indicating an age no younger than 2.4 Ma for the top of the sections. The upper *N. atlantica* (dextral) Zone of Spiegler and Jansen (1989) are only recorded in well 15/12-3 (central North Sea), but sediments corresponding to this zone are most likely present in wells 2/4-C-11 (central North Sea), 6607/5-1 (Utgard High), 7117/9-1, 7117/9-2 and 7316/5-1 (western Barents Sea continental margin). This is probably also the case for ODP 986D situated in deep water on the continental slope of the Svalbard Margin, but only the lower part of the Upper Pliocene has been thoroughly examined in this borehole. However, a short stratigraphical break between Pleistocene and Upper Pliocene is probably present in all except the central North Sea wells and the ODP 986D borehole. The uppermost Upper Pliocene is probably also present on the outermost margin in the northern parts of the North Sea, offshore Møre and in the Møre Basin. In some of these areas, one may also expect to find the most complete Pleistocene sediment packages. These are deep-water areas to which glaciers did not reach, such that glacio-isostatic sea-level fall did not result in substantial erosion.

Most Upper Pliocene and Pleistocene sections consist of clay-rich diamictons containing ice rafted pebbles of both sedimentary and crystalline composition. Some intervals consist of sandy diamictons. The exceptions to this are the lower parts of wells 2/4-C-11 and 15/12-3 in the central North Sea. In well 2/4-C-11 the lower part consists of clay and in well 15/12-3 of a well sorted sand. The lithologies observed in most sections are similar to glaciomarine sediments recorded in the Norwegian Sea which were studied by Jansen and Sjøholm (1991) and Fronval and Jansen (1996). These studies revealed traces of ice rafted material in sediments as old as 12.6 Ma. The frequency of ice rafted material increases during the period 7.2–6.0 Ma, but remains relatively low between 6.0 and 2.75 Ma. A large increase in the supply of such materials after about 2.75 Ma reflects the marked expansion of northern European glaciers (Fig. 4). 2.75 Ma is taken as the maximum age of the Late Pliocene section in all wells except for the lower parts of the sections in the central North Sea wells 2/4-C-11 and 15/12-3. In these wells both benthic foraminiferal and lithological evidence indicate deposition in the early part of the Late Pliocene (3.5–2.7 Ma), before the expansion of the northern European glaciers began. Vail and Hardenbol (1979) describe an extensive drop in global sea-levels during the period 4.1–2.9 Ma. This regression appears to have resulted in the erosion of much of the Norwegian continental shelf, with the exception of deeper water areas in the Central and Viking Graben.

5.2.3. Regional synthesis

Seismic profiles of the Upper Pliocene show that these sediments prograde from the east with distinct, shallow-angled clinoforms. Regional seismic mapping indicates that the Upper Pliocene changes character towards the north. North of approximately 58°N, the sequence is thicker and exhibits a more distinct progradation from land with a depocentre developed closer to the Norwegian mainland. Thick, glacially derived Upper Pliocene prograding shelf sediments extend along the continental margin of the northern parts of the North Sea and the Norwegian Sea shelf. These deposits are truncated in the east by the angular Pleistocene unconformity, and become thinner along the lower part of the continental slope. In the Møre Basin and in the area northeast of the Utgard High (Norwegian Sea continental shelf), these sediments reach close to 1500 m in thickness (Eidvin et al., 1998a; Figs. 1 and 7). In the southwestern parts of the Barents Sea, the Upper Pliocene forms extremely large submarine fans on the continental slope to the west of the Barents Sea shelf. The largest depocentres, with thicknesses close to 2500 m, are located west of the Bjørnøya and Storfjord Troughs (Figs. 1 and 8; Eidvin et al. 1993, 1998b; Eidvin & Nagy, 1999). The seismic reflector at the base of these fans can be traced to the Svalbard Margin and ODP Site 986 where it has been dated to <2.6 Ma by means of magnetostratigraphic methods (Channell et al., 1999).

Differences in Pliocene and Pleistocene depositional patterns are probably the result of changes in glaciation cycles that occurred approximately 1.1 Ma. During the period prior to this, glacial cycles had durations of approximately 41,000 years. After about 0.9 Ma, following a transition phase at 1.1 Ma, the dominant cycle durations increased to approximately 100,000 years. Both glacial and interglacial periods were most intense during the last period (Prell 1982, Ruddiman et al. 1986 and Berger & Jansen, 1994). During the period prior to approximately 1.1 Ma the Fennoscandian ice cap probably extended only to the present coast line (Jansen & Sjøholm, 1991). Subsequent to approximately 1.1 Ma, glaciers periodically extended over the continental shelf and transported sediments over greater distances (Sejrup et al., 1995, 1996; King et al., 1996). However, deep erosional canals at the base of the Upper Pliocene in the Bjørnøya area (Fig. 1) indicate that glaciers had already reached far on to the shelf at this time (Sættem et al., 1992). Similarly, a base Upper Pliocene section in well 7316/5-1 from the same area indicate that the deposits are derived from a melt water delta from a nearby glacier (Eidvin et al., 1998b).

5.3. Lower Pliocene

5.3.1. Microfossil assemblages

The Lower Pliocene is observed in wells 2/4-C-11 (Ekofisk Field) and 15/12-3 (Sleipner area) from the central part of the North Sea (Fig. 1). In well 2/4-C-11 these sediments correspond to benthic foraminiferal assemblages CE-FB (lower part) and CE-GB (upper part), and the planktonic assemblage CE-DP (lower part). In well 15/12-3 the Lower Pliocene corresponds to benthic assemblage CS-EB (upper part) and the planktonic assemblage CS-DP (lower part; Tables 1 and 2; Figs. 1–3(a)). Sediment of earliest Early Pliocene age may also be present in the uppermost parts of foraminiferal assemblages (N-C1) in the northern North Sea wells 34/4-6, 34/4-7 (Snorre Field), 34/8-1, 34/8-3A (Visund Field), 34/2-4 and in assemblage N-C2 in well 34/7-1 (Snorre Field; Table 3; Figs. 1 and 2).

5.3.2. Correlation with the deep sea record

The planktonic foraminiferal fauna in the central North Sea wells 2/4-C-11 and 15/12-3 correlates with the *N. atlantica* (sinistral) Zone of Spiegler and Jansen (1989). However, this zone spans the Late Pliocene to Late Miocene and no planktonic foraminiferal event in the Norwegian Sea marks the Upper/Lower Pliocene boundary (Fig. 4; Spiegler and Jansen, 1989). The identification of Lower Pliocene deposits is based on benthic foraminifera (Eidvin et al., 1999). The presence of the lowermost Lower Pliocene in the northern North Sea is based on strontium age determinations (Eidvin and Rundberg, in press).

5.3.3. Regional synthesis

The Lower Pliocene is relatively thin in wells situated in the Ekofisk and the Sleipner areas. The Miocene/Pliocene boundary does not have any clear seismic expression, but the Lower Pliocene is interpreted to thin gradually northwards in the central North Sea (Eidvin et al., 1999). In the same manner as the lower part of the Upper Pliocene, most of the Lower Pliocene is absent from the wells further north.

The Early Pliocene was a period of high relative global sea-levels (Vail & Hardenbol, 1979), and it is likely that little sediment was deposited in most areas of the Norwegian shelf. Most of the Lower Pliocene sediments, which may have existed, were probably eroded in the subsequent period during an extensive relative fall in the global sea-level (4.1-2.9 Ma; Vail & Hardenbol, 1979).

5.4. Upper Miocene

5.4.1. Microfossil assemblages

Upper Miocene deposits are recorded in central North Sea wells 2/4-C-11 (Ekofisk Field) and 15/12-3 (Sleipner area) (Fig. 1). In well 2/4-C-11, these deposits correspond to benthic foraminiferal assemblages CE-GB (lower part) and CE-HB (upper part). Planktonic fossil assemblages include CE-EP, CE-FP, CE-GP and CE-HP (upper part). In well 15/12-3 these deposits correspond to benthic assemblages CS-EB (lower part) and CS-FB. Planktonic fossil assemblages include CS-EP and CS-FP (upper part) (Tables 1 and 2; Figs. 2 and 3(a)).

In the northern North Sea, very thin Upper Miocene sections are known from wells 34/4-6, 34/4-7, 34/7-1 (Snorre Field), 34/8-1, 34/8-3A (Visund Field) and 34/2-4 corresponding to foraminiferal assemblages N-C1 and N-C2 (well 34/7-1) (Table 3; Figs. 1–3(a)).

On the Norwegian Sea continental shelf, Upper Miocene sediments are recorded in wells 6506/12-4 and 6607/5-1 (Fig. 1). In well 6506/12-4 these sediments correspond to the foraminiferal assemblages M-G, M-H and M-I. In well 6607/5-1 the Upper Miocene corresponds to the fossil assemblages M-H, M-I, M-J and M-K (upper part) (Table 4; Figs. 2 and 3(b)).

5.4.2. Correlation with the deep sea record

In the ODP/DSDP deep sea boreholes on the Vøring Plateau the Upper Miocene planktonic foraminiferal and *Bolboforma* assemblages are characterised by the lower *N. atlantica* (dextral) Zone and the *N. acostaensis* Zone of Spiegler and Jansen (1989) as well as the *B. metzmacheri* Zone and the *B. fragori*/*B. subfragori* Zone (upper part) of Müller and Spiegler (1993). The *B. metzmacheri* Zone is described from deposits with an age of approximately 10.0–8.7 Ma. The *B. fragori*/*B. subfragori* Zone is known from deposits with an age of approximately 11.9–10.3 Ma from the North Atlantic and the Vøring Plateau (Fig. 4; Spiegler & Müller, 1992; Müller and Spiegler, 1993). According to Berggren et al. (1995) the Middle/Late Miocene boundary is at 11.2 Ma.

All the index fossils from these zones are recognised in the central North Sea wells 2/4-C-11 and 15/12-3 (Eidvin et al., 1999). The Upper Miocene sections in the northern North sea wells 34/2-4, 34/4-6, 34/4-7, 34/7-1, 34/8-1 and 34/8-3A contain only scarce *N. atlantica* (dextral) (Eidvin and Rundberg, in press). All the index fossils from these zones are also recognised in the Upper Miocene section of well 6607/5-1 (Utgard High). In well 6506/12-4 (Halten Terrace) the section contains *N. atlantica* (dextral) and *N. acostaensis* (Eidvin et al., 1998a).

5.4.3. Regional synthesis

The thickest Upper Miocene sequences are found in wells located in the central North Sea and on the Norwegian Sea continental shelf. In the northern North Sea wells the Upper Miocene is thin and condensed.

In the central North Sea the Lower Pliocene, the Upper Miocene and the uppermost Middle Miocene form a single seismic unit. In the Ekofisk area, the section appears as approximately horizontal, parallel and rather continuous reflectors. The section thickens into the Central Graben depocentre, but there are no clear indications of progradation direction. In the Sleipner area, the unit is thin and it is locally strongly deformed, apparently by unstability of the underlying clays. Local structures are interpreted as onlaps and internal boundaries. The change in seismic character is related to the facies shift from the clayey succession in the south to the sandy Utsira Formation in the north. To the east the unit thins and is truncated by the base Pleistocene unconformity (Fig. 5(a) and (b); Eidvin et al., 1999).

Thin glauconitic beds represent the Upper Miocene in the northern North Sea wells. These beds are not well resolved on seismic sections, but are readily identified on wireline logs. They may drape over parts of the main Utsira sands as illustrated in Fig. 6, or may partly interdigitate with these. The main body of the Utsira sands is not penetrated by any of the wells used in the present study. However, preliminary results from a study of this almost totally fossil-barren unit in well 35/11-1 indicate a Late Miocene and possible a latest Middle Miocene age. In those areas where the Utsira sands are absent the glauconitic beds lie above Lower Miocene or Oligocene strata. To the north and northeast, the Miocene is entirely absent due to severe Pliocene incision and erosion, but equivalent sequences are probably present to the west of the Agat Field and west of the Møre margin (Eidvin and Rundberg, in press). The relation between the glauconitic beds and the Utsira Formation of the central North Sea has not been investigated in this study.

On the Norwegian Sea continental shelf, the Upper Miocene and the uppermost Middle Miocene compose one seismic unit. The seismic reflectors within this unit are often parallel, but exhibit minor faults and dome structures. The layers are truncated at a very low angle by the base of Upper Pliocene unconformity. Towards the east the unit becomes thinner (Fig. 7). The sediments consist primarily of claystone with small proportions of sand and silt (Eidvin et al., 1998a).

5.5. Middle Miocene

5.5.1. Microfossil assemblages

Middle Miocene deposits are recorded in central North Sea wells 2/4-C-11 (Ekofisk Field) and 15/12-3 (Sleipner area; Fig. 1). In well 2/4-C-11 these sediments correspond to benthic foraminiferal assemblages CE-HB (lower part) and CE-IB. Planktonic fossil assemblages include CE-HP (lower part) and CE-IP. In well 15/12-3 the Middle Miocene corresponds to the benthic assemblages CS-GB and CS-HB. Planktonic fossil assemblages include CS-FP (lower part), CS-GP and CS-HP (Tables 1 and 2; Figs. 2 and 3(a)).

Further north, the Middle Miocene sediments are only present in the well 6607/5-1 from the Utgard High on the Norwegian Sea shelf (Fig. 1). In this well the uppermost Middle Miocene corresponds to the lower part of the fossil assemblage M-K (Table 4; Figs. 2 and 3(b)).

5.5.2. Correlation with the deep sea and other planktonic fossil records

In the ODP and DSDP boreholes on the Vøring Plateau the upper part of the Middle Miocene planktonic fossil assemblages are characterised by the *B. fragori*/*B. subfragori* Zone (lower part), the *B. compressispinosa* Zone and the *B. badenensis*/*B. reticulata* Zone of Müller and Spiegler (1993). According to Spiegler & Müller (1992) and Müller and Spiegler (1993) the *B. subfragori* - *B. fragori* Zone is described from deposits with an age of approximately 11.9-10.3 Ma and the *B. badenensis*/*B. reticulata* Zone from deposits with an age of approximately 14–11.9 Ma. The *B. compressispinosa* Zone, situated between these zones, is very thin and is probably difficult to detect when working with ditch cutting samples (Fig. 4). As mentioned previously, in sediments older than these zones the calcareous fossils in the ODP and DSDP boreholes on the Vøring Plateau are for the most part dissolved (Henrich, 1989; Spiegler and Jansen, 1989; Müller and Spiegler, 1993). However, planktonic foraminifera from the lower part of the Middle Miocene are known from the North Atlantic (DSDP Leg 49; Poore, 1979) and the North Sea (King, 1989; Gradstein and Bäckström, 1996). The *Globigerina praebulloides–Globigerinoides quadrilobatus triloba* Assemblage (CE-IP) in well 2/4-C-11 (Ekofisk Field) and the *G. praebulloides* Assemblage (CS-HP) in well 15/12-3 (Sleipner area) are correlated with the planktonic foraminiferal record from these areas.

An almost complete Middle Miocene column is known only from well 15/12-3. In well 2/4-C-11 to the south, the *B. badenensis*/*B. reticulata* Zone is not recorded and sediments with an age of approximately 14-11.9 Ma are absent (Müller and Spiegler, 1993; Eidvin et al., 1999). To the north, the uppermost middle Miocene deposits corresponding to the lower part of the *B. fragori*/*B. subfragori* Zone of Spiegler and Müller (1992) and Müller and Spiegler (1993) are recorded in well 6607/5-1 (Utgard High). Middle Miocene sediments are not recorded in any of the other wells investigated in this study.

5.5.3. Regional synthesis

In the central North Sea a distinct, regionally continuous reflector is present in the upper part of the Middle Miocene seismic sequence. As described above, the uppermost Middle Miocene forms a single seismic unit together with the Upper Miocene and Lower Pliocene. The part of the Middle Miocene situated below

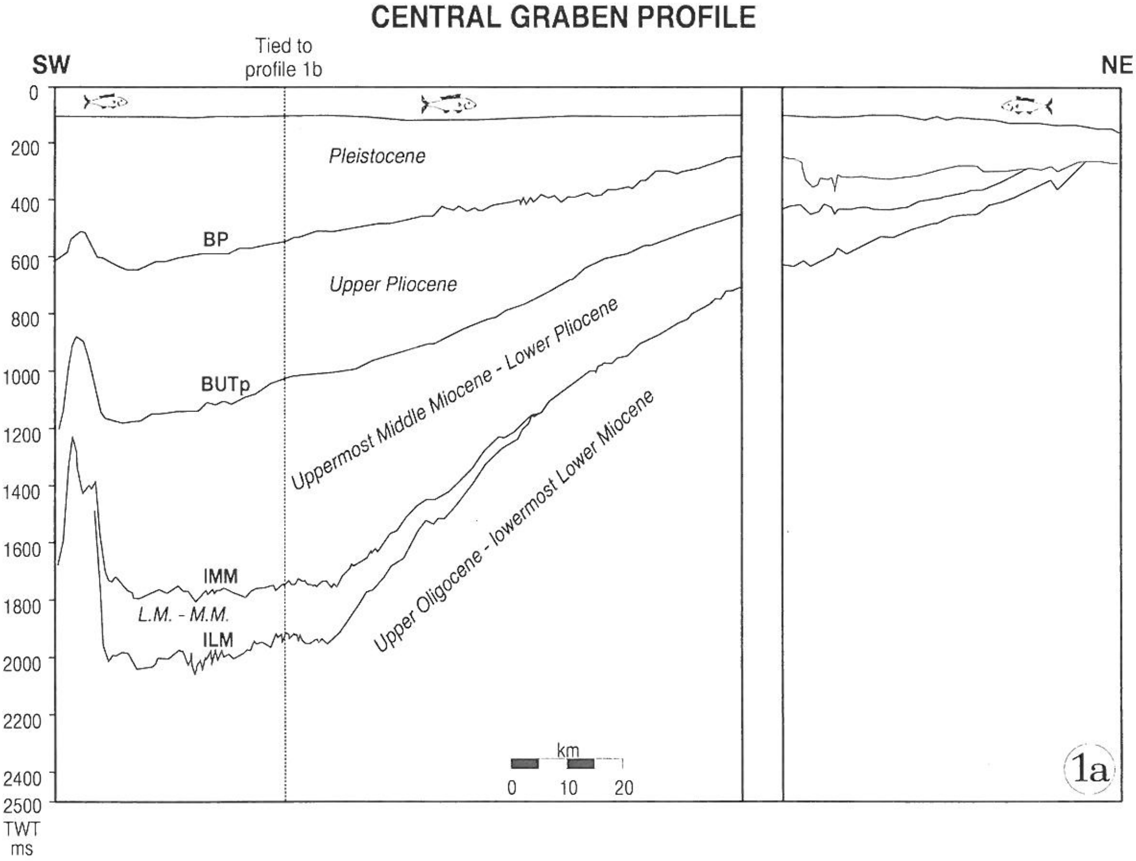

Fig. 5. (a) Geoseismic line across the Central Graben through well 2/4-C-11 (modified after Eidvin et al., 1999). Location in Fig. 1. BP = base Pleistocene, BUTp = base Upper Pliocene, IMM = intra Middle Miocene, ILM = intra Lower Miocene, UMM-LP = uppermost Middle Miocene to Lower Pliocene, LM-MM = Lower to Middle Miocene, UO-MM = Upper Oligocene to Middle Miocene. (b) Geoseismic line along the Central Graben through wells 15/12-3 and 2/4-C-11 (revised from Eidvin et al., 1999).

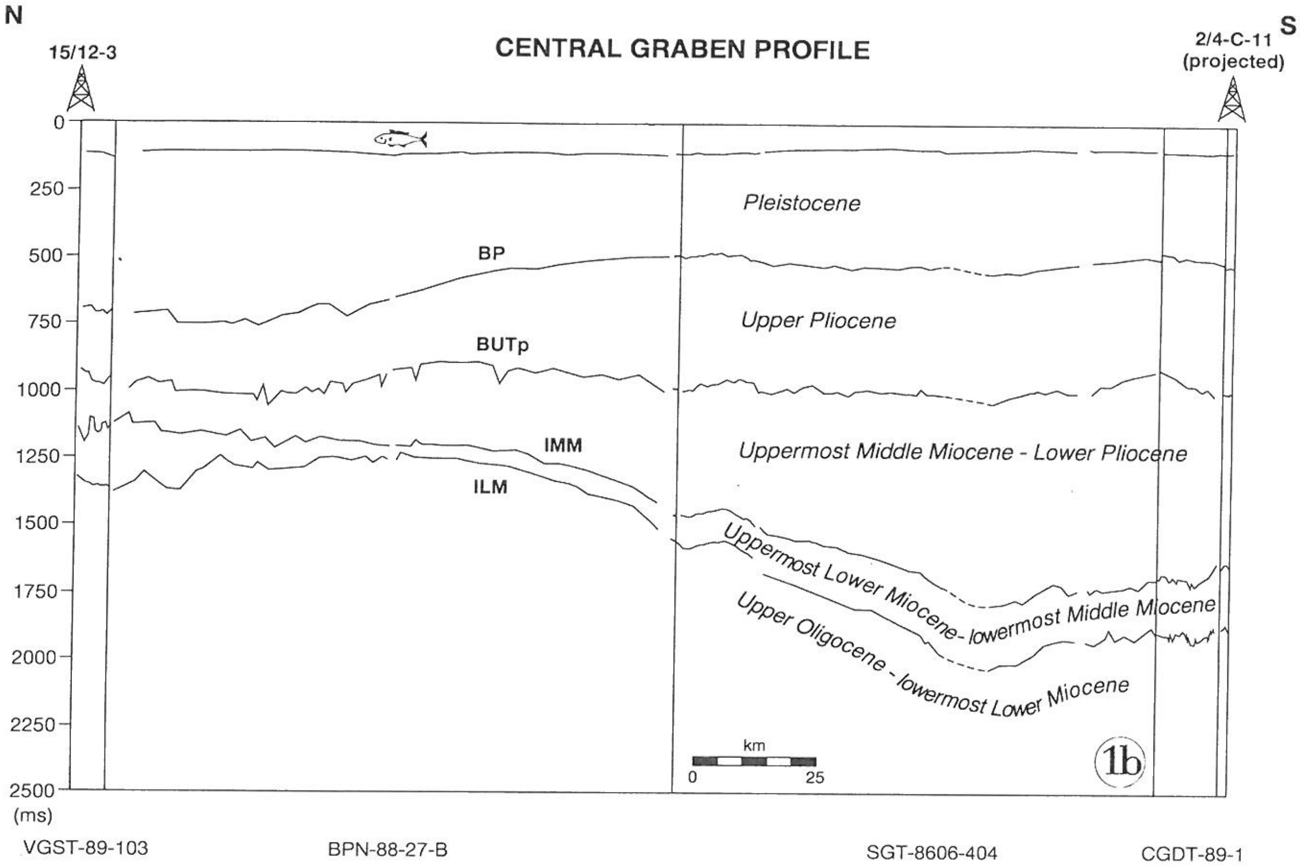

Fig. 5 (*continued*)

this reflector forms a single seismic unit together with the upper part of the Lower Miocene. This unit is clayey and exhibits small-scale faulting in both the Ekofisk and the Sleipner areas. The unit is quite thin in the area between Ekofisk and Sleipner. It is best developed in the Central Graben depocentre and thins out towards the east (Fig. 5(a) and (b); Eidvin et al., 1999).

As described above, on the Norwegian Sea continental shelf the uppermost Middle Miocene forms one seismic unit together with the Upper Miocene.

The stratigraphic break in the Ekofisk well 2/4-C-11 and the strong reflector tied to the Sleipner well 15/12-3 (possibly related to a small hiatus), together with the lack of Middle Miocene sediments in most of the other wells, are probably the result of a tectonic phase with regional uplift of a magnitude sufficient to affect the entire continental shelf (Riis, 1996; Brekke, in press).

5.6. *Lower Miocene*

5.6.1. *Microfossil assemblages*

Lower Miocene deposits are best developed in the central North Sea wells 2/4-C-11 and 15/12-3 (Fig. 1). In well 2/4-C-11 these sediments correspond to benthic foraminiferal assemblages CE-JB, CE-KB, CE-LB and CE-MB (upper part). Planktonic fossil assemblages include CE-JP and CE-KP. These assemblages are separated by a large interval with no planktonic index fossils. In well 15/12-3 the Lower Miocene corresponds to the benthic assemblages CS-IB, CS-JB, CS-KB and CS-LB (upper part). Planktonic fossil assemblages include CS-IP and CS-JP (Tables 1 and 2; Figs. 2 and 3(a)).

In the northern North Sea the lower part of Lower Miocene is recorded in wells 34/8-1 and 34/8-3A corresponding to the fossil assemblage N-E, and in well 34/8-3A also to assemblage N-D (Table 3; Figs. 1–3(a)).

In the Bjørnøya West area (Fig. 1) Lower Miocene deposits are recorded in well 7316/5-1 designated as the benthic foraminiferal assemblage BB-FC (upper part) (Table 6; Fig. 1–3(b)).

5.6.2. *Correlation with the deep sea and other planktonic fossil records*

The *Globigerina ciperoencis* Assemblage (CE-JP) in well 2/4-C-11 and the *Globigerina ciperoensis–Globigerina woodi* Assemblage (CS-IP) in well 15/12-3, both from the upper part of the Lower Miocene, are correlated with the planktonic foraminiferal record of the

North Atlantic (DSDP Leg 49; Poore, 1979). The Diatom sp. 4 Assemblages in wells 2/4-C-11 (CE-KP), 15/12-3 (CS-JB), 34/8-1 (N-D) and 34/8-3A (N-D) are correlated with the Diatom sp. 4 Zone (NSP 10) of King (1983) from the North Sea.

5.6.3. Regional synthesis

In the central North Sea wells a distinct, regionally continuous seismic reflector is present in the upper part of the Lower Miocene interval. However, biostratigraphic data does not reveal any stratigraphic break related to this reflector. As described above, the part of the Lower Miocene situated above this reflector forms a single seismic unit together with the lower part of the Middle Miocene. That part of the Lower Miocene interval situated below the reflector has not been investigated in this study.

In the northern North Sea, the Lower Miocene comprises a seismically well-defined sequence reaching about 200 m in thickness in the basin centre (Fig. 6). The base is marked by onlap onto the irregular top Oligocene nonconformity, whereas the top is identified at a prominent reflector representing the base of the sandy Utsira Formation. The succession pinches out to the east and west as illustrated in Fig. 6 and is only penetrated in the easternmost wells 34/8-3A and 34/8-1. To the north, the Lower Miocene pinches out at about 61°30′N. Southwards, the sequence gradually develop a chaotic seismic character and is more difficult to map. The Lower Miocene sequence exhibits low amplitude, continuous reflection pattern displaying an onlapping basin fill configuration (Eidvin & Rundberg, in press).

In well 7316/5-1 in the Bjørnøya West area the Lower Miocene section lies immediately below Upper Pliocene deposits. The sequence is very thin and consists primarily of clay. The seismic reflection at the base of the interval is continuous and exhibits strong amplitude across the area, defining a marked syncline to the east of the well site. West and south of the well site the reflection is truncated by the base Pliocene nonconformity. In well 7316/5-1 a thin interval situated below the Lower Miocene is given an Early Miocene to Early Oligocene age. The reflection described above may represent an intra-Miocene event or the base Miocene, but may also be associated with a larger hiatus (Fig. 8; Eidvin et al., 1998b).

5.7. Upper Oligocene

5.7.1. Microfossil assemblages

Upper Oligocene deposits are recorded in the central

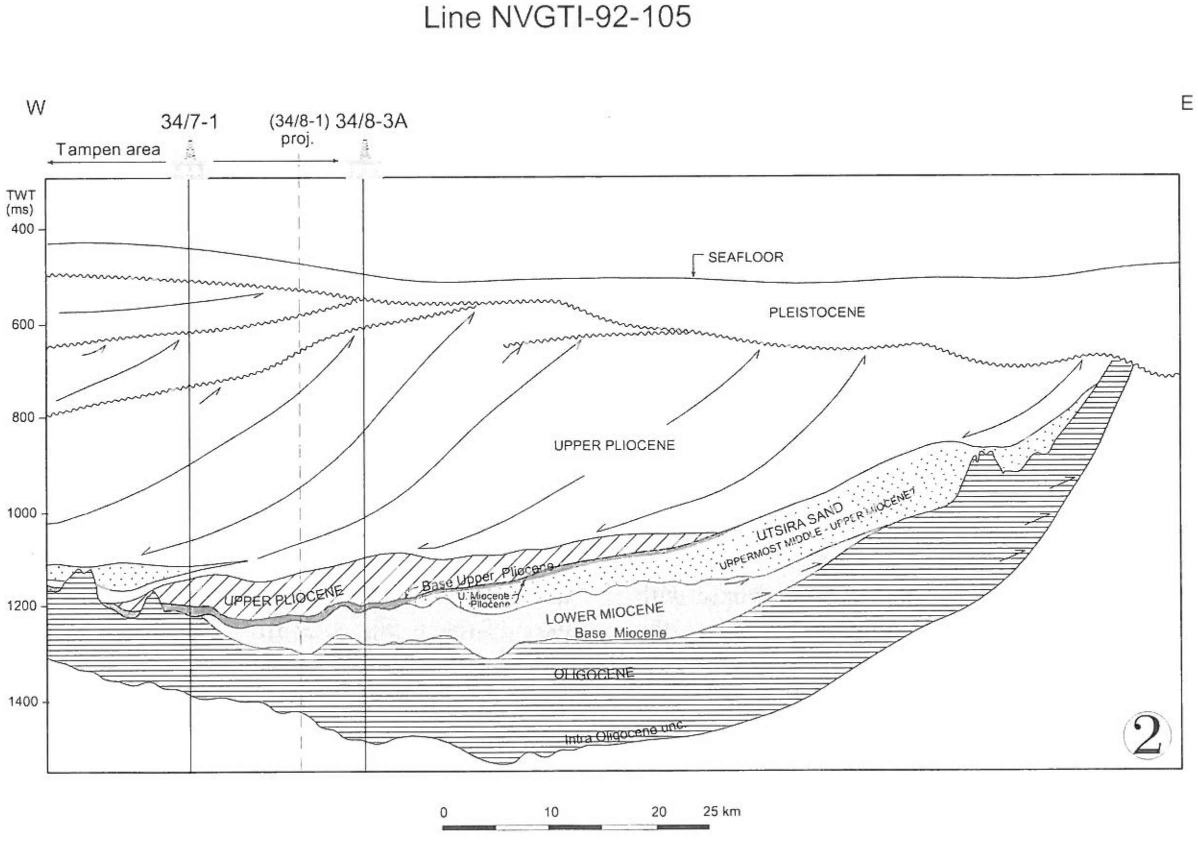

Fig. 6. Geoseismic line across the northern North Sea through wells 34/7-1 and 34/8-3A (modified after Eidvin and Rundberg, in press). Location in Fig. 1.

North Sea wells 2/4-C-11 and 15/12-3 (Fig. 1), although the base of the Upper Oligocene is not seen in any of these wells. In well 2/4-C-11 the Upper Oligocene corresponds to the benthic foraminiferal assemblage CE-MB (lower part) and the planktonic assemblage CE-LP. In well 15/12-3 the Upper Oligocene corresponds to the benthic foraminiferal assemblage CS-LB (lower part) and the planktonic assemblage CE-LP (Tables 1 and 2; Figs. 2 and 3(a)).

The lower part of the Upper Oligocene and the uppermost part of Lower Oligocene are recorded in the northern North Sea wells 34/4-6, 34/4-7, 34/7-1 (Snorre Field) and 34/8-1 (Visund Field), corresponding to the fossil assemblage N-F1. This part of the Oligocene is also recorded in well 34/8-3A (Visund Field) corresponding to the assemblage N-F2, and in well 34/2-4 corresponding to fossil assemblages N-F3 and N-F4 (Table 3; Figs. 2 and 3(a)).

On the Norwegian Sea shelf a thin interval of Upper Oligocene sediments is recorded in well 6506/12-4 (Halten Terrace) corresponding to fossil assemblage M-L (Table 4; Figs. 2 and 3(b).

5.7.2. Correlation with planktonic fossil records

The Diatom sp. 3 Assemblage in the wells 2/4-C-11 (CE-LP), 15/12-3 (CS-KB), 34/4-6, 34/4-7, 34/7-1, 34/8-1 (N-F1), 34/2-4 (N-F4) and 6506/12-4 (M-L) is correlated with the Diatom sp. 3 Zone (NSP 9c) of King (1989) from the North Sea.

5.7.3. Regional synthesis

In the central North Sea there is no well-defined seismic boundary below the intra-Lower Miocene reflector which represents the Oligocene–Miocene boundary. In the wells the Upper Oligocene sediments comprise mostly clay with small proportions of silt, sand and some limestone stringers (Eidvin et al., 1999).

In the northern North Sea the Lower-Upper Oligocene lies immediately below Upper Miocene deposits in wells 34/2-4, 34/4-6, 34/4-7 and 34/7-1, and immediately below the Lower Miocene in wells 34/8-1 and 34/8-3A. The sediments are dominated by clay and silt with minor amounts of sand (Eidvin and Rundberg, in press).

The thin interval of Upper Oligocene clay-rich sediments in well 6506/12-4 on the Norwegian Sea shelf is situated between Upper Miocene and Lower/Middle Eocene deposits (Eidvin et al., 1998a). The areal extent of the Upper Oligocene has also not been investigated in this study.

5.8. Lower Oligocene

5.8.1. Microfossil assemblages

In the northern North Sea the lower part of Lower Oligocene is recorded in well 31/3-1 (Troll Field) corresponding to the foraminiferal assemblage N-G (Table 3; Figs. 1–3(a)).

On the Norwegian Sea shelf the lowermost part of Lower Oligocene is found in wells 6610/3-1 and 6610/7-1 (Nordland Ridge). In well 6610/3-1 these deposits correspond to the foraminiferal assemblage M-M. In well 6610/7-1 the Lower Oligocene does not contain in situ microfossils, and dating is based on seismic correlation to well 6610/3-1 (Table 4; Figs. 1–3(b)).

In the western Barents Sea the lowermost part of Lower Oligocene is recorded in well 7316/5-1 (Bjørnøya West area) corresponding to the benthic foraminiferal assemblage BB-FD (Table 6; Figs. 1–3(b)).

5.8.2. Regional synthesis

In well 31/3-1 the lower part of Lower Oligocene lies immediately below the Pleistocene. Clay and silt with minor amounts of sand dominate the sediments. The areal extent of these deposits has not been investigated in this study.

In wells 6610/3-1 and 6610/7-1 on the Nordland Ridge the lowermost Lower Oligocene contains mostly sand with small, rounded pebbles. These sequences form a part of extensive depositional unit which extends parallel to the mid-Norwegian coast from Møre to Lofoten (Rokoengen et al., 1995). According to Rokoengen et al. (1995) the sediments are interpreted as deltaic and coastal deposits, probably formed in a wave-dominated environment with extensive longshore drift. The seismic profile along the Nordland Ridge (Fig. 7) shows that this sequence is represented by an interval of steeply dipping reflectors which are interpreted to be a set of prograding foresets. The base of the succession is seismically identified as a downlap surface. On the southwestern flank of the succession, flat-lying Upper Pliocene strata onlap the prograding coastal deposits. To the east the sequence becomes thinner due to erosion at its upper surface. The western boundary is a morphological ramp formed by the distal forsets (Eidvin et al., 1998a).

In well 7316/5-1 (Fig. 1) the lowermost Lower Oligocene lies immediately below a Lower Miocene–Lower Oligocene section. In this well the Lower Oligocene consists of silty clay. The profile on Fig. 8 shows that the Lower Oligocene unit appears to become thinner towards the east, but gradually thicker to the west. West of the well site, parts of the Lower Oligocene unit are eroded and rest directly beneath the base Pliocene (Eidvin et al., 1998b).

5.9. Middle Eocene

5.9.1. Microfossil assemblages

In well 7316/5-1 (Fig. 1) a thick section of sediments from the Middle Eocene has been investigated. The base of the Middle Eocene is not observed in this well. The deposits correspond to the Unzoned Interval f3 and to the foraminiferal assemblages BB-FE, BB-FF and BB-FG (Table 6; Figs. 1–3(b)).

5.9.2. Correlation with planktonic fossil records

The planktonic foraminiferal species *Pseudohastigerina* sp. and *P. micra*, recorded in assemblages BB-FE to BB-FG, have been described from Middle Eocene sections from the Netherlands (Doppert & Neele, 1983) and from the North Sea (King, 1989).

5.9.3. Regional synthesis

In well 7316/5-1 the Middle Eocene lies immediately below the Lower Oligocene. The sediments consist primarily of slightly silty claystone. Thin limestone beds are present throughout, and sand stringers and beds also occur. A very thick Middle Eocene section is observed to extend along the entire NE–SW profile illustrated in Fig. 8 (Eidvin et al., 1998b).

5.10. Lower/Middle Eocene

5.10.1. Fossil assemblages

Thin intervals of Lower/Middle Eocene sediments are recorded in the Norwegian Sea shelf wells 6506/12-4 (Halten Terrace), 6607/5-1, 6607/5-2 (Utgard High) and 6610/7-1 (Nordland Ridge). These correspond to the radiolarian *Cenosphaera* sp. Assemblage (M-N). The base of the Lower/Middle Eocene is only seen in well 6607/5-1 (Table 4; Figs. 1–3(b)).

In the western Barents Sea the Lower/Middle Eocene is recorded in well 7119/9-1 (Senja Ridge) corresponding to the *Cenosphaera* sp. Assemblage. The base of the Lower/Middle Eocene is not observed (Figs. 1–3(b)).

5.10.2. Correlation with planktonic fossil records

The *Cenosphaera* sp. Assemblage in all these wells is correlated with the *Cenosphaera* sp. Zone (NSP 6) of King (1989) from the North Sea.

5.10.3. Regional synthesis

The Lower/Middle Eocene lies immediately below the Upper Oligocene in well 6506/12-4, below the Middle Miocene in well 6607/5-1, and below the Upper Pliocene in wells 6607/5-2, 6610/7-1 and 7119/7-1 (Fig. 2). In all the wells the sediments consist primarily of claystone. The areal extent of the Lower/Middle Eocene has not been mapped.

5.11. Upper Palaeocene–Lower Eocene

5.11.1. Fossil assemblages

In the Norwegian Sea shelf uppermost Upper Palaeocene–lowermost Lower Eocene sediments are recorded in well 6610/7-2 (Nordland Ridge) corresponding to the diatom assemblage *Coscinodiscus* sp. 1 Assemblage (M-O). The base of the unit is not seen (Table 4; Figs. 1–3(b)).

In the western Barents Sea the uppermost Upper Palaeocene–lowermost Lower Eocene is recorded in wells 7117/9-2 and 7119/7-1 (Senja Ridge) corresponding to the *Coscinodiscus* sp. 1 Assemblage. The base of the units is seen in neither of these wells (Figs. 1–3(b)).

5.11.2. Correlation with planktonic fossil records

The *Coscinodiscus* sp. 1 Assemblages in all these

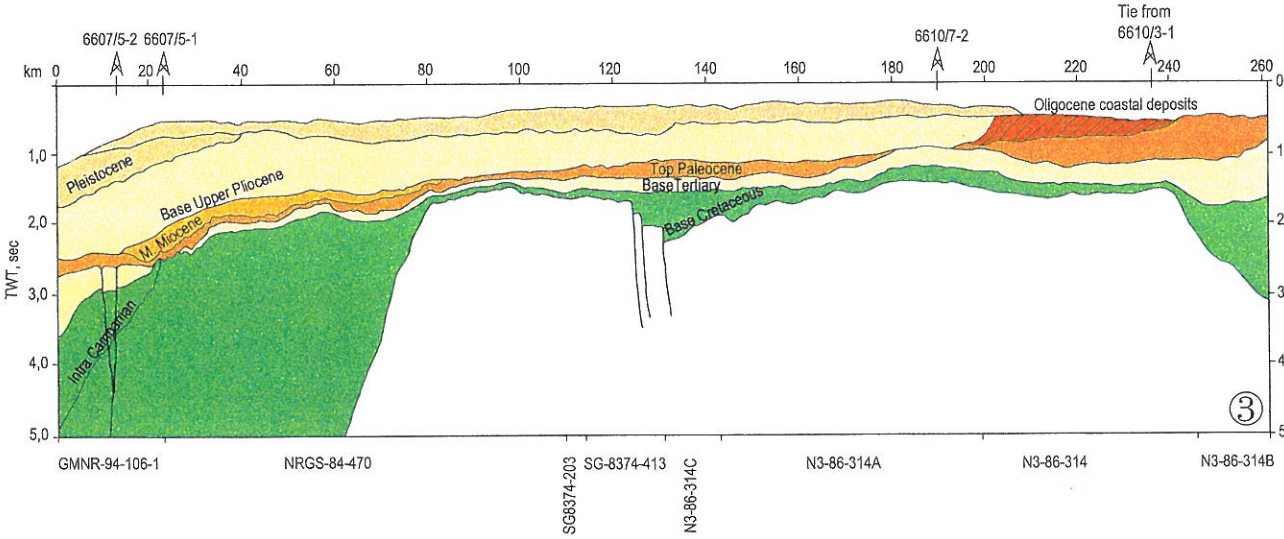

Fig. 7. Regional geoseismic line across the Utgard High and along the Nordland Ridge through wells 6607/5-1, 6607/5-2 and 6610/7-2 (modified after Eidvin et al., 1998a). M. Miocene = Middle Miocene noncomformity Location in Fig. 1.

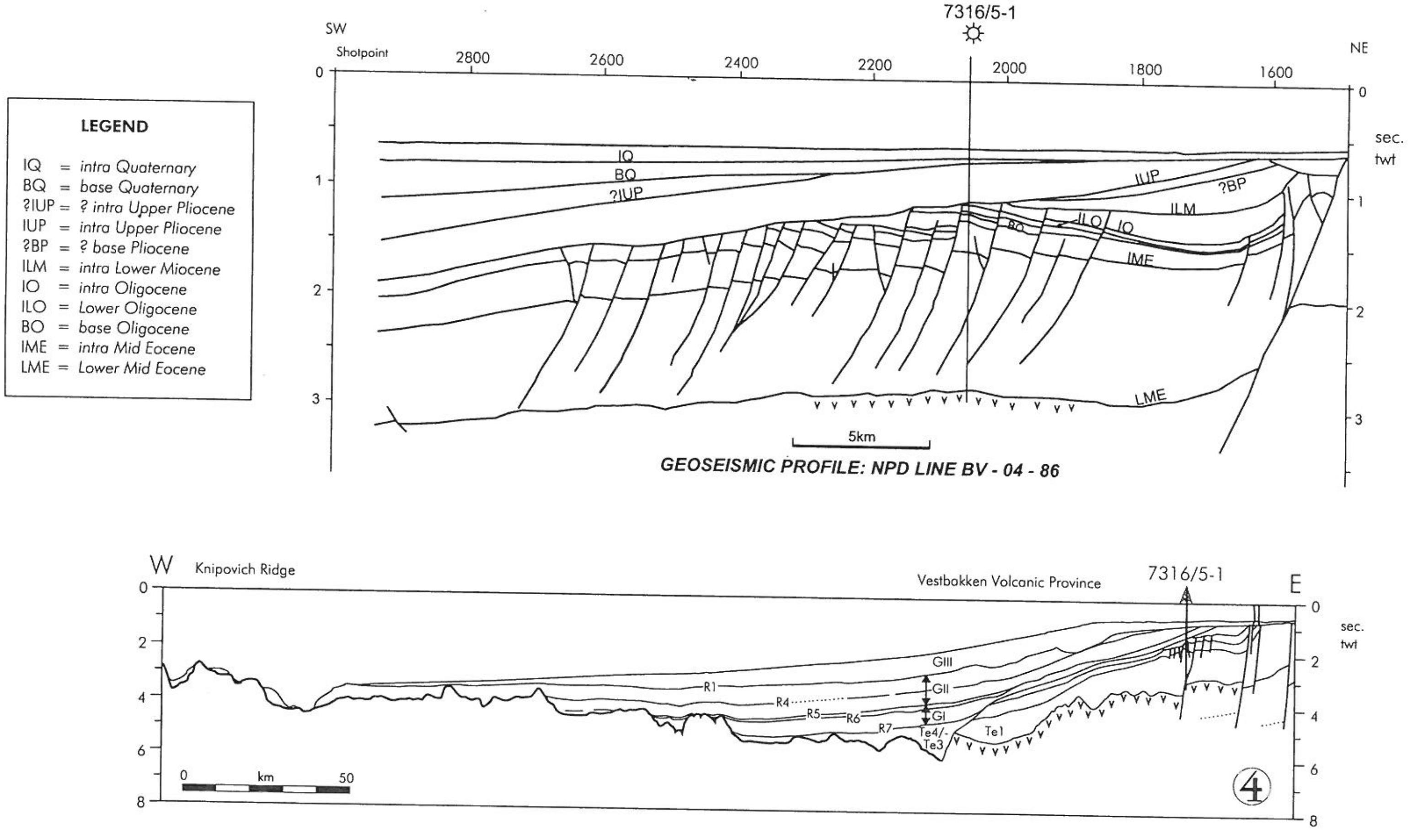

Fig. 8. The lower profile shows a regional geoseismic line across the Bjørnøya Fan through well 7316/5-1 (modified after Faleide et al., 1996). R1 to R7 = regional reflectors and GI to GIII = seismic units (according to Faleide et al., 1996). Te1, Te3 and Te4 = seismic units (according to Vorren et al., 1991). The upper profile shows details across the Vestbakken Volcanic Province (modified after Eidvin et al., 1998b). Location in Fig. 1.

wells is correlated with the *Coscinodiscus* sp. 1 Zone (NSP 4) of King (1989) and the *Coscinodiscus* spp. Zone (NSR 3) of Gradstein and Bäckström (1996) from the North Sea.

5.11.3. Regional synthesis

Where it is observed the uppermost Upper Palaeocene–lowermost Lower Eocene lies immediately below the Upper Pliocene, and consists primarily of claystone. The areal extent of these deposits have not been investigated.

6. Discussion

We have identified the main Neogene sedimentary packages along the Norwegian shelf and assigned more precise ages to these in order to elucidate the Cainozoic geological evolution of this region. The most complete Neogene succession is recorded in the Central North Sea. Further north the successions are interrupted by an increasing number of hiati of increasing duration. After a period of erosion in the late Middle to early Late Miocene there was a marked increase in the influx of terrigeneous sediment in the Late Miocene. A period of transgression in the Early Pliocene resulted in strongly reduced rates of deposition, and sediments of this age are preserved mainly in the Central North Sea. A period of regression in the earliest Late Pliocene probably resulted in erosion of most of the Norwegian continental shelf with the exception of the deeper areas of the Central and Viking Grabens. This period was immediately followed in the later part of Late Pliocene, by the rapid deposition of glacially derived sediment prograding along the entire shelf (Figs. 4, 6–8). In general, Pleistocene development is a continuation of the Late Pliocene evolution, but is marked by more extensive erosion of the inner shelf. This is inferred from the flat truncation of underlying prograding strata and the extensive build up of debris flow sediments within glacial fan depocentres (Vorren et al., 1989; King et al., 1996; Sejrup et al., 1987; Solheim et al., 1996).

The entire Neogene development is closely related to the climatic evolution of high latitude regions surrounding the North Atlantic and the Norwegian–Greenland Sea. The first signs of Northern Hemisphere glaciation, recorded in ODP sites on the Vøring Plateau (Fig. 1), probably originated in Greenland and date to ~12.6 Ma (latest Middle Miocene; Fronval & Jansen, 1996). This event is associated with a global reorganisation of ocean circulation which occurred at the same time (Wright & Miller, 1993), and marks the onset of continuous northern component deep water and the subsequent increased water mass exchange between the sub-Arctic and the world ocean. The onset of a more erosive regime on the Norwegian mainland also appears to be related to climatic development in the Miocene, although there is no evidence for the existence of glaciers on the eastern seaboard of the Norwegian-Greenland Sea during this period. There was a significant increase in the supply of ice-rafted debris to the deep ocean, associated with climatic cooling in the latest Miocene (Messinian event; Jansen and Sjøholm, 1991; Fronval & Jansen, 1996). To date, however, firm evidence for the existence of glaciers has been documented only from Greenland (Larsen et al., 1994; Jansen, Raymo, Blum et al., 1996).

The existing biostratigraphic framework consistently assigns an age of Late Pliocene to the onset of high deposition rates originating from glaciation on the eastern flanks of the Norwegian–Greenland Sea. This event is most pronounced in marine isotope stage G6 at 2.75 Ma in the later part of the Gauss magnetic epoch (Kleiven, 1995; Fronval & Jansen, 1996). The event is also recorded as an intensification of glaciation in North America, Greenland and in northern Europe, including Svalbard. There is a consistent biostratigraphic correlation between the glacial deposits recorded on the shelf and continental margin, and the deep sea drill sites. It follows that deposition of glacial fans along the entire Norwegian Margin occurred primarily during approximately the past 2.7 Ma. As is recorded at ODP Site 986 west of Spitsbergen (Fig. 1), there was a marked change in the character of deposition in the Pleistocene; from a relatively well-sorted sandy unit to a unit marked by extensive debris flows and turbidities (King et al., 1996; Sejrup et al., 1996; Solheim et al., 1999). This event reflects the movement of glaciers onto the shelf break during which time the resulting excess sediment supplied by ice streams to the upper slope gave rise to repeated debris flows.

7. Conclusions

A stratigraphic framework for the Cainozoic strata of most of the Norwegian continental shelf and margin has been developed and described. This framework is consistent for the entire margin from the central North Sea in the south to the Barents Sea in the north, and is also correlative to the deep sea record in the Norwegian Sea and North Atlantic. Because it is impossible to use standard low latitude zonation schemes to subdivide and correlate sequences for a regional stratigraphic syntheses, a more locally derived system utilising mainly planktonic and benthic foraminiferal assemblages and *Bolboforma* species has been developed. This biostratigraphic framework is generally consistent with age information from Sr-isotope analyses from the same sediment samples which were used for the microfossil analyses.

The application of this framework permits a more precise and detailed age determination of Cainozoic, and especially Neogene, strata. Some of the main advances are as follows: (1) An understanding that the major part of the massive sediment wedges on the Svalbard and western Barents Sea Margins were built up over a relatively short time period during the Late Pliocene–Pleistocene, mainly as a result of glacial erosion of the Barents Shelf. (2) Documentation of the occurrence of Lower Miocene and Lower Oligocene sediments on the western Barents Sea Margin southwest of Bjørnøya. (3) A demonstration that the thick, glacially derived Upper Pliocene–Pleistocene prograding shelf deposits extending along the continental margin of the northern North Sea and Norwegian Sea continental shelf are coeval with the sediment wedges of the Svalbard and western Barents Sea Margins. (4) The record of a hiatus at the base of the Upper Pliocene along the entire Norwegian shelf north of the central North Sea. (5) Determination of an Early Oligocene age for the deltaic and coastal deposits of the Molo Formation (informal), which are situated both beneath and to the east of the proximal part of the Upper Pliocene along the Norwegian Sea continental shelf. (6) Documentation that the Utsira Formation of the central North Sea was deposited in the period earliest Late Miocene to earliest Late Pliocene. (7) Documentation that sediments interpreted to constitute the upper part of the Utsira Formation of the Tampen area (northern North Sea), which were referred to the Late/Middle Miocene by Eidvin and Riis (1992), Gradstein et al. (1992) and other workers, consist partly of glacially derived Upper Pliocene deposits. (8) Documentation of an uppermost Middle/lowermost Upper Miocene hiatus along the Norwegian shelf from the central North Sea to the Norwegian Sea continental shelf.

Acknowledgements

This paper is published with the permission of the Norwegian Petroleum Directorate. The authors acknowledge Halliburton Geophysical Services and Geco-Prakla for permission to publish seismic lines. They extend their thanks to Finn Moe, Bjørg Ruus, Sigrun Torrissen and Inger M. Våge for careful and accurate technical assistance and to Rune Goa and Astrid Larsen for preparation of the illustrations. The authors acknowledge the benefit of discussions with Fridtjof Riis and Robert Williams. They are grateful to Jenö Nagy and Felix Gradstein whose comments improved the manuscript. Thanks are also due to Tony Doré and one anonymous reviewer for their important comments.

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Paper 2:
Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields)

Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields)

TOR EIDVIN, FRIDTJOF RIIS & YNGVE RUNDBERG

Eidvin, T., Riis, F. & Rundberg, Y.: Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). *Norsk Geologisk Tidsskrift*, Vol. 79, pp. 97–128. Oslo 1999. ISSN 0029-196X.

The investigation is based on analyses of planktonic and benthonic foraminifera and *Bolboforma* carried out in the uppermost Palaeogene and Neogene of the production well 2/4-C-11 (56°33′ N, 3°13′ E) on the Ekofisk Field and the exploration well 15/12–3 (58°14′ N, 1°53′ E) on the Sleipner Field. The analyses are based primarily on ditch cuttings, but in well 2/4-C-11, 49 sidewall cores and six short conventional cores were also available. Strontium isotope and paleomagnetic analyses were also carried out in well 2/4-C-11. A 420 m-thick accumulation of Lower Miocene sediments is present in the Ekofisk area. The Middle Miocene comprises approximately 180 m, and the Upper Miocene is represented by an approximately 500 m-thick interval. A hiatus is present in the Middle Miocene, and the middle part of the Middle Miocene is missing. A thin interval (approximately 120 m) of Lower Pliocene sediments is found overlying the Upper Miocene. Uppermost, a thick accumulation of Upper Pliocene–Pleistocene sediments (approximately 1000 m) is in place. More than half of this was deposited during the Pleistocene. The entire Upper Pliocene is represented in this area. This contrasts to the northern North Sea, as well as areas further north, where sediments of this epoch are partially missing in a hiatus comprising the lowermost part of the Upper Pliocene. In the Sleipner area the Lower and Middle Miocene are approximately 160 m and 180 m thick, respectively. The Upper Miocene (approximately 100 m) and the Lower Pliocene (approximately 40 m) thin from the Ekofisk towards the Sleipner Field. Uppermost, an approximately 900 m-thick succession of Upper Pliocene–Pleistocene sediments is present. Nearly two-thirds of this accumulation are Pleistocene in age.

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Introduction

The study area is located in the intra-cratonic North Sea Basin (Fig. 1). The central North Sea is a key area for studying Upper Cainozoic sediments on the Norwegian continental shelf. This area has subsided almost throughout the entire period, allowing more than 2 km of mostly marine clastic sediments to accumulate. Jordt et al. (1995) subdivided the Cainozoic of the Norwegian sector of the North Sea into 10 seismic sequences and documented large hiati in Pliocene and Miocene deposits. In the Neogene, major hiati are related to tectonic events in the Middle Miocene and to the climatic changes causing glaciation in the Late Pliocene and Pleistocene. Precise dating is important in order to obtain a reliable correlation between the preserved Neogene successions within the North Sea. Understanding of the Neogene geological development is necessary to construct basin models and to analyse the Late Cainozoic tectonism and glaciation of the region.

In the present study, the Neogene sections are almost complete. Consequently, the wells from this area are well suited for a detailed biostratigraphical analysis, and they allow the study of sediments not present further north and east.

The primary objective of this combined biostratigraphic and seismostratigraphic study is to date the sediments and main seismic sequence boundaries. A secondary objective is to interpret depositional environments based on microfaunal contents. Using the various dating and correlation methods available (Sr-isotope, paleomagnetic analyses, planktonic foraminifera, etc.), our effort was placed on applying the most effective methods according to the stratigraphic level under investigation. Emphasis was placed on correlating planktonic fossil fauna with fossil zones from ODP/DSDP sites in the Norwegian Sea, as these zones are paleomagnetically calibrated. The study of well 2/4-C-11 is based on that of Eidvin et al. (1993b), but it has been updated and revised.

Absolute ages used in the biostratigraphic schemes and strontium isotope seawater curves are based on Berggren et al. (1985). For comparison purposes, fossil zonation schemes correlated to absolute ages of Berggren et al. (1995) are also shown.

In order to ensure that the results reported here are consistent with electric logs and other technical information, all depths are expressed as meters below the rig floor (mRKB).

Previous work

Many hydrocarbon exploration and production wells have been drilled in the Norwegian, British and Danish sectors in the central North Sea. Most of these wells were analysed by biostratigraphic consultants, but none of these routine biostratigraphic studies are publicly available. Traditionally, the Upper Cainozoic has not been given high priority, and consequently, the dating is often insufficient. This applies particularly to the earliest drilled wells.

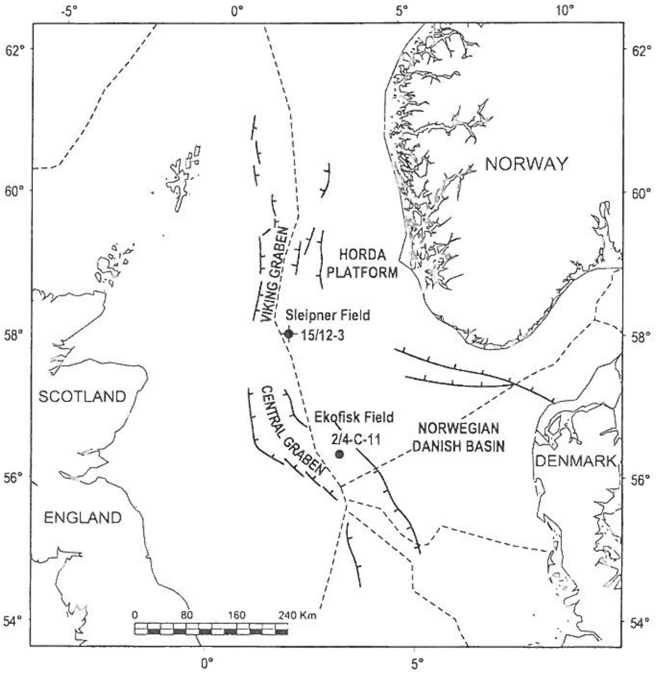

Fig. 1. Location of investigated wells. Main structural features are after Bjørslev Nielsen et al. (1986). Stippled lines show boundaries between national sectors.

Based on material from numerous wells, King (1983, 1989) published a general foraminiferal zonation for Cainozoic sediments, which comprises the whole North Sea area. Gradstein & Bäckström (1996) provide a similar zonation for the North Sea and Haltenbanken areas.

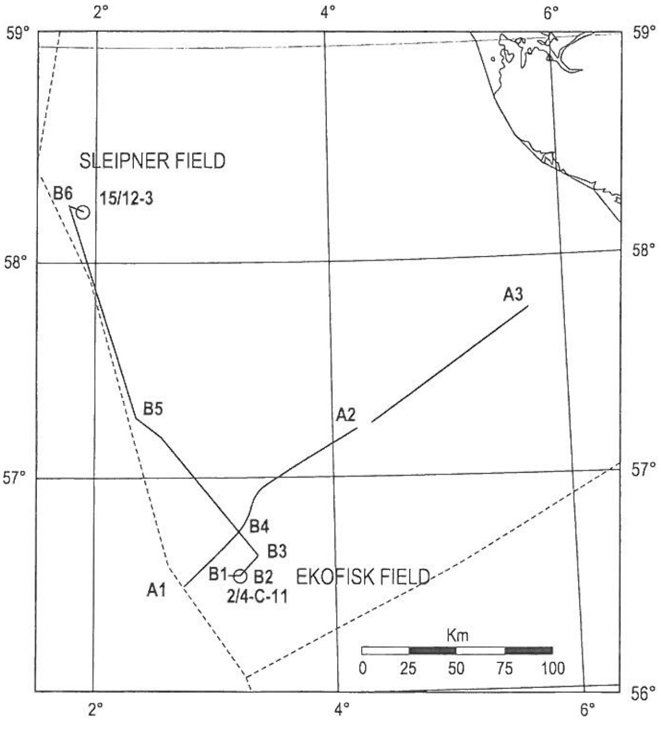

Fig. 2. Map showing wells and seismic lines. Stippled lines show boundaries between national sectors.

Redatings of Cainozoic sediments in exploration and production wells were published by Gradstein & Berggren (1981), Moe (1983), Knudsen & Asbjörndottir (1991) (Upper Pliocene and Pleistocene), Gradstein et al. (1992, 1994), Eidvin et al. (1993b), Michelsen et al. (1994), Konradi (1996) and Laursen et al. (1997). Pedersen (1995) made a biostratigraphic study of the Upper Pliocene/Pleistocene boundary based on a number of exploration wells from the central North Sea. Cores from a Pleistocene geotectonic drilling on the Fladen area have been investigated by Sejrup et al. (1987).

Important regional seismic studies were carried out by Bjørslev Nielsen et al. (1986), Cameron et al. (1987, 1993), Jensen & Schmidt (1992), Jordt et al. (1995), Michelsen et al. (1994), Sørensen & Michelsen (1995) and Sørensen et al. (1997).

Seismic interpretation

As an additional support to the correlation, the two studied wells were tied together by regional 2D seismic lines. Four main seismic sequence boundaries were identified, tied to the wells and interpreted along the transects shown in Fig. 2. The resulting seismic profiles (Figs. 3, 4) show the time thickness variations in the Neogene succession, and indicate a Neogene depocenter in the 2/4-C-11 area.

The wells have been tied by synthetic seismograms provided by the operators. In well 2/4-C-11, a direct correlation cannot be made, because the seismics do not cover the platform area, and because a gas chimney was present above the field. This problem was resolved by tying the well 2/4-B-19 in the northern part of the field to the seismics, and then correlating the logs between wells 2/4-B-19 and 2/4-C-11.

Pleistocene

The BP (base Pleistocene) reflector is the lower boundary of a heterogeneous succession. In the thick, basinal areas, Pleistocene reflection patterns are commonly continuous and parallel. Such a pattern is interpreted as typical for glacio-marine sediments. In the upper 2–300 milliseconds, deep erosional channels occur at different levels, and are most abundant in the Norwegian-Danish Basin. Because of their great and variable depths (200 m or more), the larger channels have been tentatively interpreted as subglacial features (Dangerfield 1992; Sejrup et al. 1991). In the uppermost parts of this sediment package, and in the eastern parts of profile A1–A3 (Fig. 3), the Pleistocene sequence is characterized by discontinuous reflections, indicating a stronger glacial influence on the sediments.

The BP reflector itself is defined as the boundary between the heterogeneous Pleistocene reflectors and the prograding Upper Pliocene succession. The exact location of the reflector is not always easy to identify, particularly in the westernmost areas where the Pliocene progradation

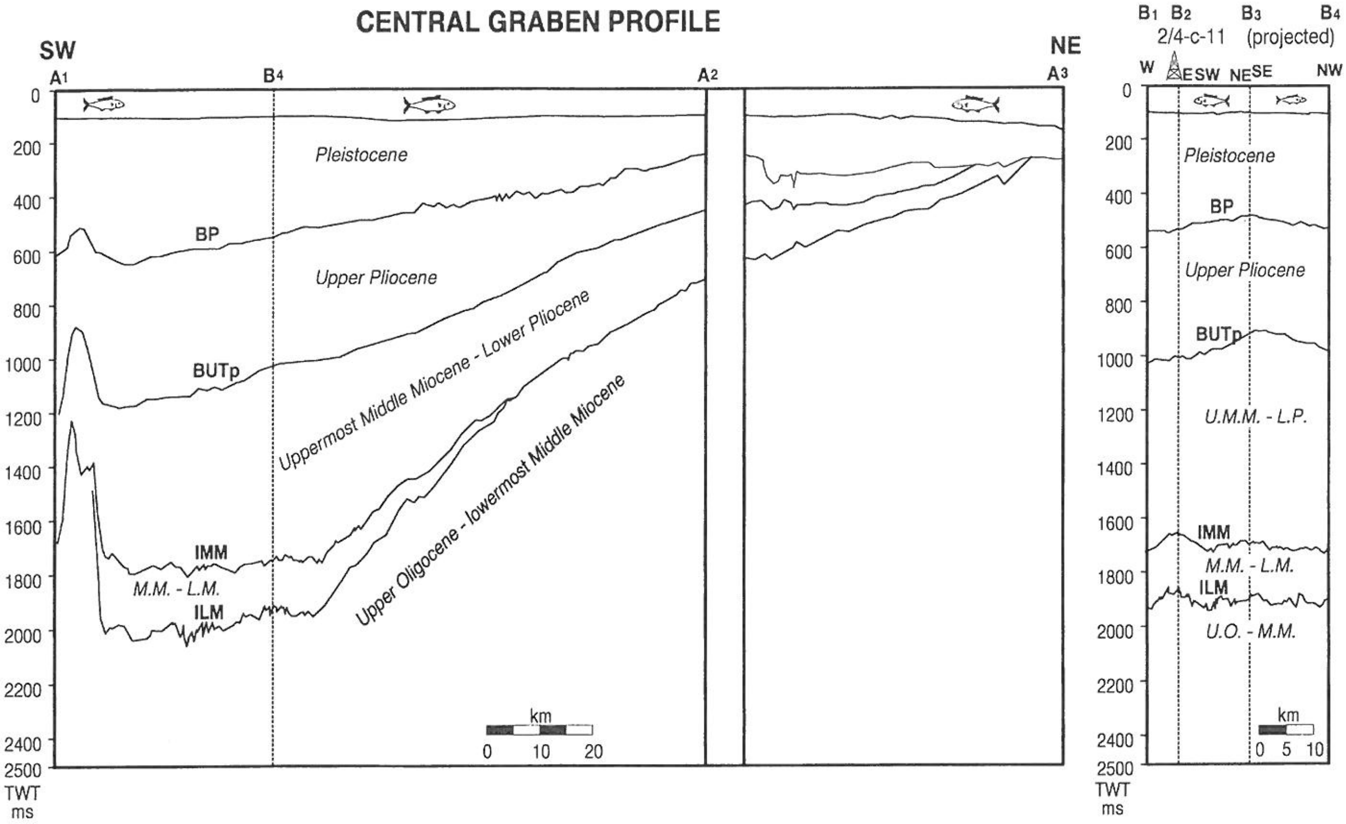

Fig. 3. Interpreted seismic line across the Central Graben through well 2/4-C-11. BP = base Pleistocene, BUTp = base Upper Pliocene, IMM = intra-Middle Miocene, ILM = intra-Lower Miocene, UMM-LP = uppermost Middle Miocene to Lower Pliocene, MM-LM = Middle to Lower Miocene, UO-MM = Upper Oligocene to Middle Miocene.

is poorly defined. A weak onlap on the BP reflector is indicated along the margins of the Pleistocene depocenter.

The BP reflector is correlated to the base of the Pleistocene in the wells analysed. In well 2/4-C-11, the logs and sediment samples show no significant difference between the sections dated to Pleistocene and Late Pliocene, respectively. In well 15/12–3, the BP reflector is correlated to the top of a section with higher velocities than the overlying clays.

Upper Pliocene

The BUTp (base Upper Pliocene) reflector is the base of a seismic section which shows progradation from the east. Low angle clinoforms with rather good continuity are typical for most of the area covered by the profiles (Fig. 2). The westernmost parts seem to be in a distal position relative to the source area, and here the clinoforms are very gently dipping or give way to parallel, nearly horizontal reflections.

The BUTp reflector is correlated to the base of the Upper Pliocene in the wells. In 2/4-C-11 logs, the reflector is picked at the base of a section with upward coarsening, silty clay succession. In 15/12–3, the reflector corresponds to the top of the sands of the Utsira Formation.

Profile B1–B6 (Fig. 4) shows the decreasing thickness of the Upper Pliocene clays from the Central Graben depocenter towards the Sleipner area. In the northern part of the profile, some channel-like features are noted in the lower part of the sequence. Across these features, reflectors seem to be deformed into synclines, which were filled in with flat-lying sediments. The seismic pattern indicates soft sediment deformation involving the underlying Upper Miocene–Lower Pliocene sediments. Soft sediment deformation is extensively developed further north, in the Utsira Formation.

Upper Miocene and Lower Pliocene

The IMM (intra-Middle Miocene) reflector is a prominent seismic boundary which corresponds to the boundary between the Hordaland and Nordland Groups. In the Sleipner area, the seismic unit between the BUTp and IMM reflectors comprises mainly the sandy Utsira Formation, and its character is very different from that of the Ekofisk area.

In the Ekofisk area, the Upper Miocene to Lower Pliocene section consists of parallel, rather continuous, close to horizontal reflectors. The section thickens into the Central Graben depocenter, but there are no clear indications of any direction of progradation. At its base, a faint onlap has been observed on the lower boundary at IMM. In the Ekofisk area, the section may be tentatively divided into a lower part with more continuous internal reflections

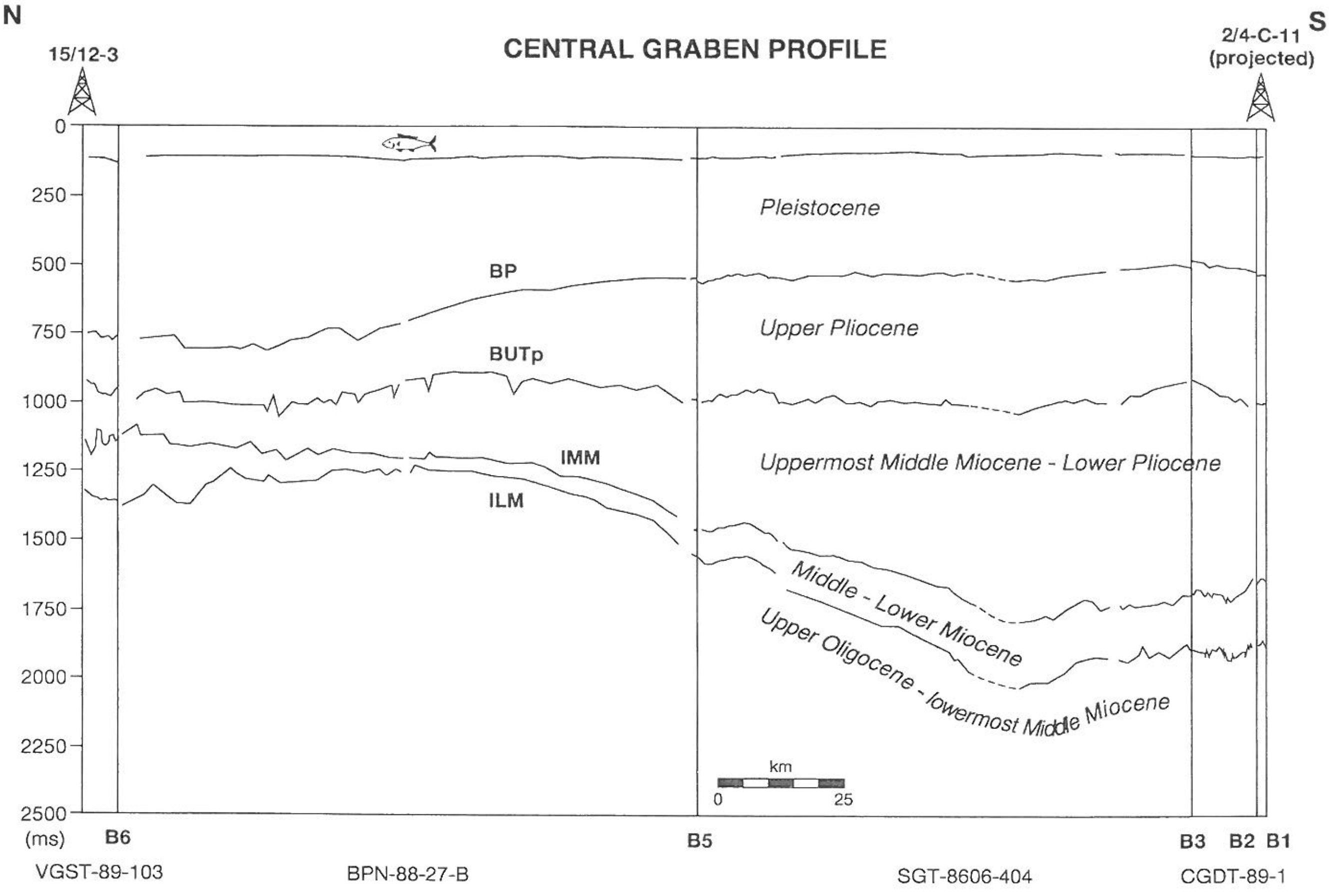

Fig. 4. Interpreted seismic line along the Central Graben through wells 15/12–3 and 2/4-C-11. BP = base Pleistocene, BUTp = base Upper Pliocene, IMM = intra-Middle Miocene, ILM = intra-Lower Miocene.

and an upper part with less continuity. This change takes place within the Upper Miocene, and the Miocene–Pliocene boundary does not seem to have any seismic expression.

At the lower boundary of the interval, the IMM reflector is well defined by a conspicuous change in internal deformation, the underlying unit being strongly faulted. It is known from regional mapping that the IMM reflector commonly defines the top of gas chimneys and that it coincides with the latest phase of major salt movement in the Central Graben. Pressure build-up above hydrostatic commonly starts downhole at the IMM unconformity. However, above the major chalk fields, gas chimneys and undercompacted clays are also encountered in the Upper Miocene and Lower Pliocene succession.

In the Sleipner area, the Upper Miocene and Lower Pliocene succession is thin, and it is locally strongly deformed, apparently by movement of the underlying clays. Locally, onlaps and internal boundaries can be interpreted. The difference in seismic character is related to the facies shift from the clay succession in the south to the sandy Utsira Formation in the north. The IMM reflector at the base of the succession is a deformed surface with variable reflection strength. It corresponds to the base of the Utsira Formation.

In profile B1–B6 (Fig. 4), the deformation of the Miocene in the northern part of line BPN-88-27 coincides with the distribution of the Utsira Formation, which is well constrained by well data. We suggest that the deposition of the sand loaded and facilitated drainage of pore water in the underlying clay, causing synsedimentary deformation.

It should also be noted that the correlation of the BUTp reflector from the south to the north is not straightforward because of the deformation and facies shifts. Biostratigraphic data show that the base of the Upper Pliocene is situated within the Utsira Formation, while the seismic boundary is interpreted on the top of the formation. However, a detailed interpretation is difficult, and much more seismic work would be required to define the exact relation between the upper part of the Utsira Formation and the lower parts of its clay-rich equivalent in the south.

Middle and Lower Miocene

The unit between the ILM (intra-Lower Miocene) and IMM reflectors belongs to the upper part of the Hordaland Group. The ILM reflector is typically developed as the top of a set of strong, continuous reflectors. In the Ekofisk area, the ILM reflector, although faulted, seems to form the base of several small-scale faults which deform the unit above.

Table 1. Samples analysed in wells 2/4-C-11 and 15/12-3. SWC = sidewall core, DC = ditch cutting sample, *samples not included in the range chart because of lack of space.

SAMPLES ANALYSED IN WELL 2/4-C-11

190.0 m SWC	713.3 m DC	1325.9 m DC	1719.9 m Core*
238.0 m SWC	731.5 m DC	1342.0 m SWC	1724.9 m Core
249.0 m SWC	737.0 m SWC	1344.2 m DC	1728.2 m DC
313.0 m SWC	749.8 m DC	1362.0 m SWC*	1745.0 m SWC*
330.0 m SWC	766.0 m SWC	1362.5 m DC	1746.5 m DC
342.0 m SWC	768.1 m DC	1380.7 m DC	1764.8 m DC
347.0 m SWC	786.4 m DC	1400.0 m SWC	1783.1 m DC
360.0 m SWC	804.7 m DC	1405.0 m SWC	1792.0 m SWC
369.0 m SWC	812.0 m SWC	1408.2 m DC	1801.4 m DC
373.0 m SWC*	823.0 m DC	1426.5 m DC	1819.7 m DC
374.7 m Core*	859.5 m DC	1453.9 m DC	1837.9 m DC
374.9 m SWC	877.8 m DC	1472.2 m DC	1852.3 m SWC
383.2 m DC	914.4 m DC	1481.3 m DC	1856.7 m DC
399.0 m SWC	932.7 m DC	1486.0 m SWC	1874.5 m DC
402.0 m SWC	951.0 m DC	1494.0 m SWC	1911.1 m DC
408.0 m SWC	965.0 m SWC	1499.6 m DC	1929.4 m DC
411.0 m DC	978.4 m DC	1517.9 m DC	1953.8 m SWC
421.0 m SWC	996.7 m DC	1536.2 m DC	1956.8 m DC
429.8 m DC	1004.0 m SWC	1556.0 m SWC*	1975.0 m DC
436.0 m SWC	1015.0 m DC	1554.5 m DC	2002.5 m DC
457.0 m SWC*	1033.3 m DC	1557.7 m Core*	2020.5 m DC
457.2 m DC	1051.6 m DC	1559.6 m Core*	2039.1 m DC
475.5 m DC	1069.8 m DC	1563.2 m Core*	2057.4 m DC
487.0 m SWC	1077.0 m SWC	1561.5 m Core*	2084.8 m DC
502.9 m DC	1088.1 m DC	1563.6 m DC	2112.3 m DC
528.2 m Core*	1115.6 m DC	1581.9 m DC	2121.4 m DC
530.3 m DC	1133.9 m DC	1600.2 m DC	2148.8 m DC
535.4 m Core	1161.3 m DC	1618.5 m DC	2167.1 m DC
531.9 m Core*	1166.0 m Core	1629.0 m SWC	2194.6 m DC
540.0 m SWC	1163.4 m Core*	1636.8 m DC	2203.7 m DC
557.7 m DC	1162.6 m Core*	1655.1 m DC	2220.0 m DC
568.0 m SWC	1160.9 m Core*	1664.7 m DC	2240.3 m DC
576.0 m SWC*	1188.7 m DC	1672.0 m SWC*	2258.6 m DC
576.0 m DC	1197.9 m DC	1673.4 m DC	2276.9 m DC
594.5 m DC	1225.3 m DC	1679.0 m SWC	2303.1 m Core*
621.8 m DC	1243.6 m DC	1691.6 m DC	2298.7 m Core
632.0 m SWC*	1261.9 m DC	1707.0 m SWC	2304.3 m DC
630.9 m DC	1280.2 m DC	1709.9 m DC	2322.6 m DC
658.4 m DC	1293.0 m SWC	1710.7 m Core*	2340.9 m DC
665.0 m SWC	1302.0 m SWC	1712.5 m Core*	2357.3 m SWC
676.7 m DC	1307.0 m SWC*	1714.6 m Core	2368.3 m DC
685.8 m DC	1307.6 m DC	1718.2 m Core*	
707.0 m SWC	1314.0 m SWC	1722.2 m Core	

SAMPLES ANALYSED IN WELL 15/12-3

200.0 m DC	620.0 m DC	970.0 m DC	1280.0 m DC
220.0 m DC	640.0 m DC	980.0 m DC	1290.0 m DC
240.0 m DC	660.0 m DC	1000.0 m DC	1300.0 m DC
260.0 m DC	680.0 m DC	1010.0 m DC	1310.0 m DC
280.0 m DC	700.0 m DC	1020.0 m DC	1320.0 m DC
300.0 m DC	720.0 m DC	1040.0 m DC	1330.0 m DC
320.0 m DC	740.0 m DC	1060.0 m DC	1340.0 m DC
340.0 m DC	760.0 m DC	1080.0 m DC	1360.0 m DC
360.0 m DC	780.0 m DC	1100.0 m DC	1370.0 m DC
380.0 m DC	790.0 m DC	1110.0 m DC	1380.0 m DC
400.0 m DC	800.0 m DC	1120.0 m DC	1400.0 m DC
420.0 m DC	820.0 m DC	1140.0 m Dc	1420.0 m DC
440.0 m DC	840.0 m DC	1150.0 m DC	1430.0 m DC
460.0 m DC	850.0 m DC	1160.0 m DC	1440.0 m DC
480.0 m DC	860.0 m DC	1180.0 m DC	1450.0 m DC
500.0 m DC	880.0 m DC	1200.0 m DC	1460.0 m DC
520.0 m DC	890.0 m DC	1220.0 m DC	1480.0 m DC
540.0 m DC	900.0 m DC	1240.0 m DC	1500.0 m DC
560.0 m DC	920.0 m DC	1250.0 m DC	1520.0 m DC
580.0 m DC	940.0 m DC	1260.0 m DC	
600.0 m DC	960.0 m DC	1270.0 m DC	

In the Sleipner area, the ILM reflector commonly defines the base of synsedimentary deformation. The unit between the ILM and IMM thins to the east, and is best developed in the Central Graben depocenter. Fig. 4 shows that the unit is thin in an area between Sleipner and Ekofisk. The ILM reflector can be identified with rather high confidence across this saddle area. Seismically, there is no well-defined boundary below the ILM reflector corresponding to the Oligocene–Miocene boundary.

Material and methods

Micropaleontological analyses

From both wells 2/4-C-11 and 15/12–3, ditch cutting samples were obtained with a 10-m sampling interval through most of the examined sections. In well 2/4-C-11, six conventional cores were taken at the following intervals: 373.5–374.8 m, 527.3–535.7 m, 1160.7–1166.2 m, 1556.9–1563.2 m, 1710.5–1725.5 m and 2297–2305.2 m. Forty-nine sidewall cores were also available from this well. These were taken at variable intervals throughout the investigated section. All the sidewall cores, 21 samples from the conventional cores and most of the available ditch cutting samples were analysed for planktonic and benthonic foraminifera. In addition, the Middle to Upper Miocene section was also analysed for *Bolboforma* (calcareous cysts), and the Upper Oligocene to Lower Miocene section was analysed for diatoms (Table 1).

When drilling with exploration rigs, the sampling does not commence before the well has reached a depth of ca. 100 m below the sea floor. Consequently, the uppermost 84 m of well 2/4-C-11 and 89 m of well 15/12–3 could not be analysed.

For analyses of conventional core samples and the cuttings, 50–100 g material were used. Only 10–20 g were available from the sidewall cores. The fossil identifications were carried out in the 106–500 μm fraction. In some samples the fractions <63–106 μm and >500 μm were also investigated. Whenever possible, 300 individuals were picked from each sample. In order to identify the microfossil assemblages better, several samples rich in mineral grains were also gravity-separated in a heavy liquid. Consequently, in fossil-rich samples, 1000–1500 individuals were inspected. The stratigraphically important fossils are reported in the range charts in Figs. 5a and b and 7a and b. Eidvin et al. (1993b) present range charts of all registered species in well 2/4-C-11, but without some modifications performed in this study. Complete range charts for well 15/12–3 can be obtained from the first author.

Other analyses

Strontium isotope analyses were performed by the Institute for Energy Technology, Kjeller, Norway, on calcareous material (i.e. mainly tests of calcareous foraminifera and *Bolboforma*). The analysed material was mainly taken from sidewall cores, but conventional core material and one ditch cutting sample, all from well 2/4-C-11, were also included. Ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$ ratio to a global strontium isotope curve.

The lithologic analyses are based on visual examination, both of the samples prior to treatment and of the dispersed and fractionated material after preparation. Petrophysical logs were also employed in the descriptions.

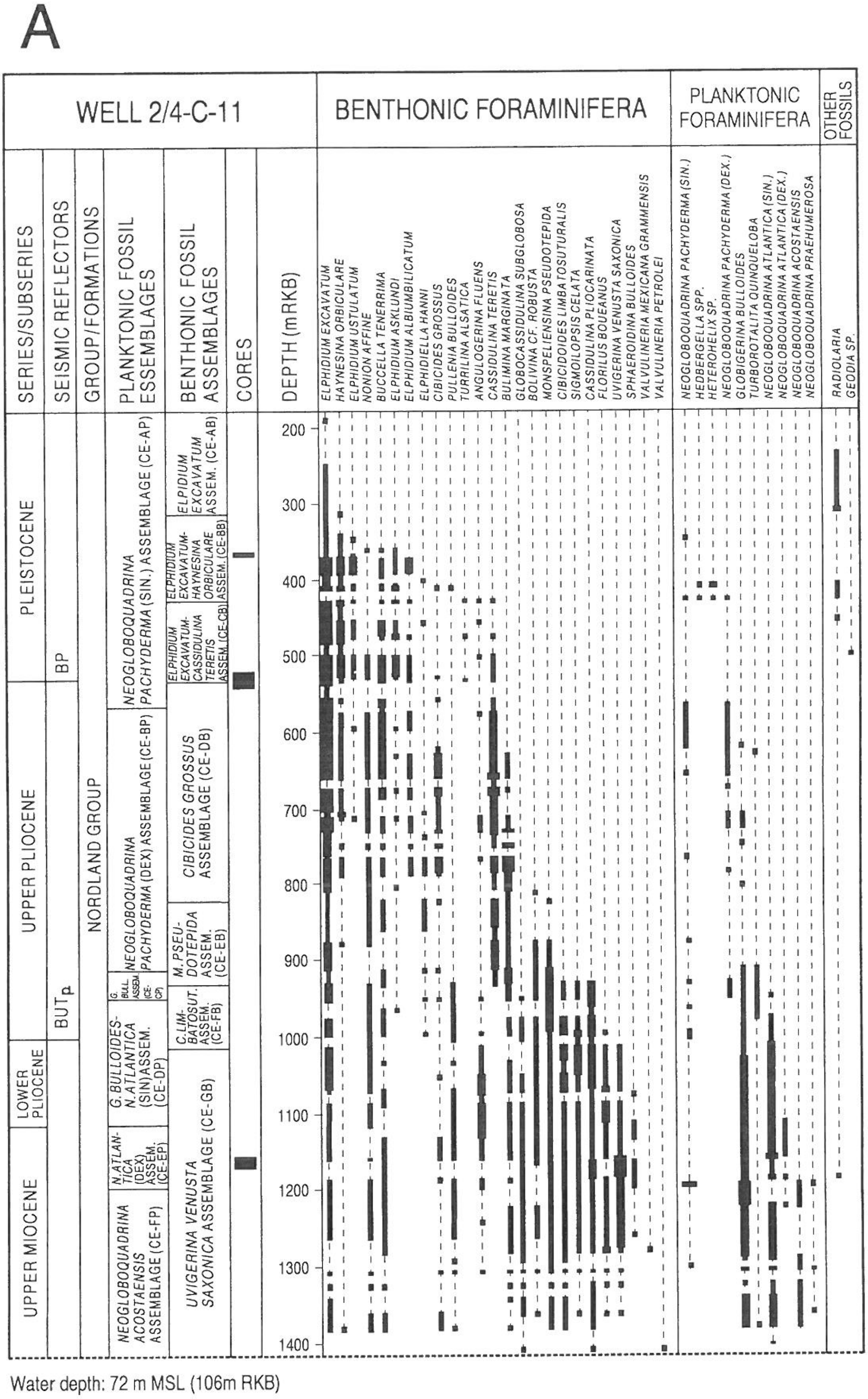

Fig. 5a. Range chart of the stratigraphically important microfossils in the upper part of the investigated interval of well 2/4-C-11. BP = base Pleistocene, BUTp = base Upper Pliocene, mRKB = meters below rig floor, mMSL = meters below mean sea level.

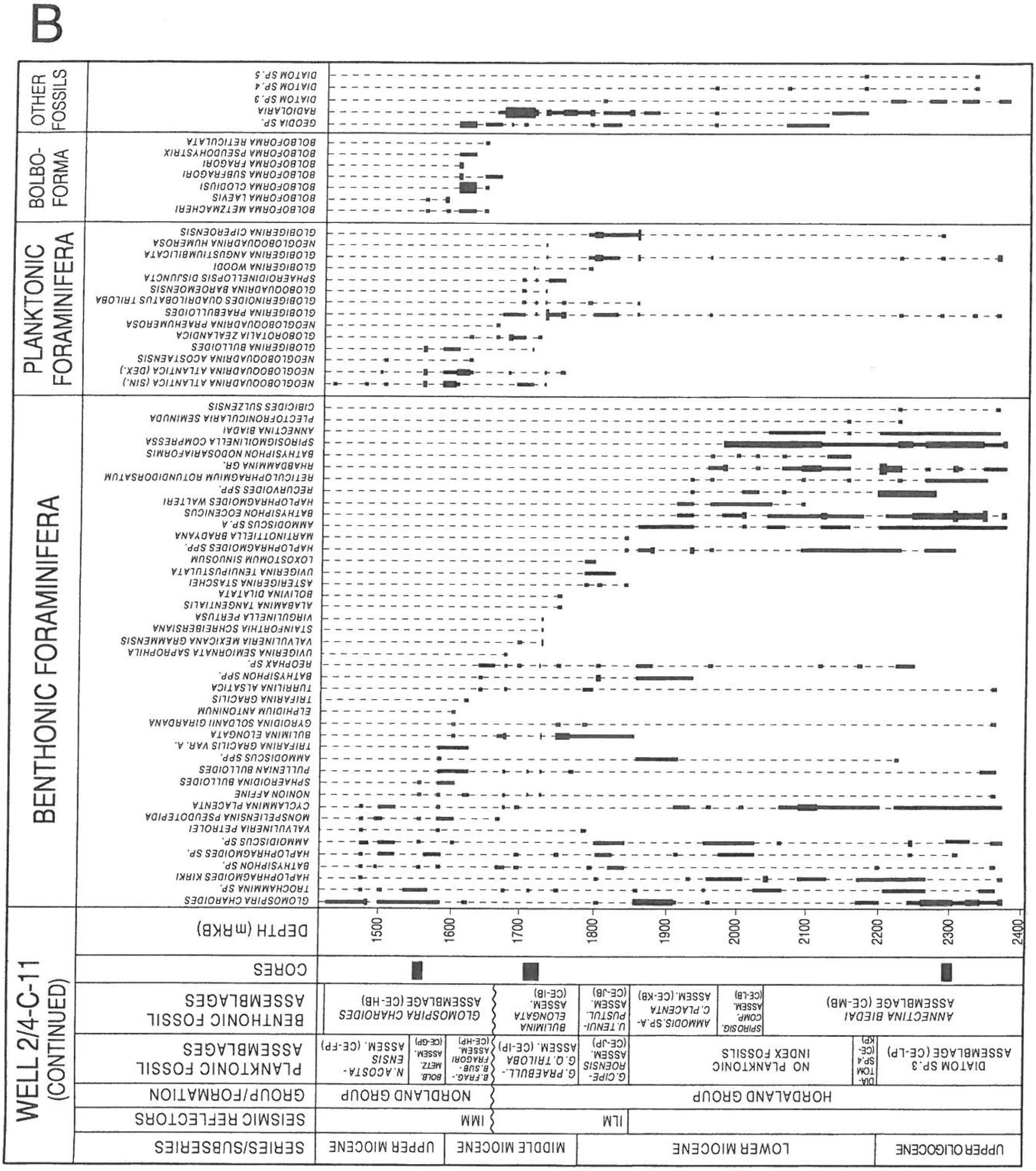

Fig. 5b. Range chart of the stratigraphically important microfossils in the lower part of the investigated interval of well 2/4-C-11. IMM = intra-Middle Miocene, ILM = intra-Lower Miocene, mRKB = meters below rig floor.

Paleomagnetic analyses were performed by CB-Magneto, Stavanger, Norway on material from the two uppermost conventional cores (373.5–374.8 m and 527.2–535.7 m).

Biostratigraphic correlation

The standard Cainozoic biostratigraphic scheme is based on planktonic foraminifera and calcareous nannoplankton established for tropic and subtropic areas. Towards the north the assemblages become progressively less diverse, and many key species are missing in the North Sea (King 1983).

The fossil assemblages in the wells 2/4-C-11 and 15/12-3 are primarily correlated with the biozonation of King (1983, 1989), where a micropalaeontological zonation for Cainozoic sediments of the North Sea is outlined.

Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken is also extensively used. In the Pleistocene sections the work of Knudsen & Asbjörndóttir (1991) is used. In addition, several articles that describe benthonic foraminifera from onshore basins from the area surrounding central and southern North Sea are used. Correlation with the planktonic foraminifer zones of Poore (1979), Weaver (1987), Weaver & Clement (1986, 1987) and Spiegler & Jansen (1989) and the *Bolboforma* zones of Quale & Spiegler (1989), Spiegler & Müller (1992) and Müller & Spiegler (1993), established through ODP/DSDP drilling in the Norwegian Sea and the North Atlantic, is especially important for dating of the sediments. Correlating with these zones may also yield quite accurate ages, since the zones are calibrated with nannoplankton and paleomagnetic data. The zonations of King (1983, 1989) and Gradstein & Bäckström (1996) are based on the last appearance datums (LADs) of the various taxa. The zonations of planktonic foraminifera and *Bolboforma* from the ODP/DSDP drilling are based on the first appearance datums (FADs). It is important to note that King (1989) was published prior to the publications of ODP Leg 104 on the Vøring Plateau in the Norwegian Sea. Consequently, the ages of King's planktonic foraminifer and *Bolboforma* zones differ somewhat from the ages of corresponding planktonic foraminifer zones of Spiegler & Jansen (1989) and *Bolboforma* zones of Quale & Spiegler (1989), and especially the revised *Bolboforma* zonation of Müller & Spiegler (1993).

The fossil assemblages are somewhat different in the two investigated areas. The main difference is a larger proportion of agglutinated forms in Miocene and Oligocene deposits in the Ekofisk area compared to the Sleipner site. Consequently, we describe the faunal trends at each site separately.

Stratigraphy of well 2/4-C-11

Fossil assemblages

In this well, a system of 13 assemblages based on benthonic foraminifera (CE-AB to CE-MB) and 12 assemblages based on planktonic fossils (CE-AP to CE-LP) is devised. The boundaries between the assemblages are based on the LADs of selected taxa, which have been chosen because of their chronostratigraphic importance. Most of the selected taxa have well-documented, consistent ranges on a regional scale. The assemblages are described from top to base of the succession, following the order in which they are normally encountered in offshore borehole studies. Abbreviations of the assemblage designations are as follows: C = Central North Sea, E = Ekofisk Field, B = Benthonic and P = Planktonic (Figs. 5a, b, 8, 9).

Benthonic assemblages

ELPHIDIUM EXCAVATUM ASSEMBLAGE

Designation: CE-AB.

Definition: The top of the assemblage extends to the uppermost investigated sample (190 m). The base is marked by the highest occurrence of *Haynesina orbiculare*.

Depth range: 190–313 m.

Material: Three very small sidewall cores.

Age: Middle to Late Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone NSB 17 of King (1983) and probably Zones Jo 4 and Jo 5 of Knudsen & Asbjörndóttir (1991).

Description: Very few foraminifera occur in these small sidewall cores. Rare occurrences of *E. excavatum* and *Elphidium* sp. are the only representatives (Fig. 5a).

Remarks: This interval contains so few foraminifera that it is difficult make a good correlation. However, the assemblage is clearly of Pleistocene age (see below).

ELPHIDIUM EXCAVATUM – HAYNESINA ORBICULARE ASSEMBLAGE

Designation: CE-BB.

Definition: The top of the assemblage is taken at the highest occurrence of *H. orbiculare*. The base is marked by the highest occurrence of *Cassidulina teretis*.

Depth range: 313–429.8 m.

Material: One conventional core sample at 374.7 m, 11 sidewall cores and three ditch cutting samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).

Description: This assemblage contains a medium-rich benthonic fauna of calcareous foraminifera. *E. excavatum* and *H. orbiculare* occur most frequently. Other characteristic species include *Elphidium ustulatum*, *Buccella tenerrima*, *Elphidium asklundi* and *Elphidium albiumbilicatum* (Fig. 5a). Mollusc fragments are also common.

Remarks: The benthonic foraminifera in this assemblage are characteristic Pliocene–Pleistocene taxa. All the recorded species are extant. Knudsen & Asbjörndóttir (1991) have described an *E. excavatum – H. orbiculare* assemblage Zone (Jo 6) from the Josephine boring (30/13-2x) in the easternmost part of the British sector. Correlation based on benthonic foraminifera between 30/13-2x and the BGS borehole BH 81/34 indicates that Zone Jo 6 is slightly older than the Brunhes/Matuyama boundary (Knudsen & Asbjörndóttir 1991). BH 81/34 has been cored, and the cores have been magneto-stratigraphically investigated (Stoker et al. 1983). In well 2/4-C-11, material in the core present at 373.5–374.8 m shows reverse polarity, which supports deposition during the Matuyama Chron.

CASSIDULINA TERETIS – ELPHIDIUM EXCAVATUM ASSEMBLAGE

Designation: CE-CB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. teretis*. The base is marked by the highest occurrence of *Cibicides grossus*.

Depth range: 429.8–530.3 m.

Material: One conventional core sample at 528.2 m, three sidewall cores and four ditch cutting samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 7 of Knudsen & Asbjörndóttir (1991), Zone NSR 13 of Gradstein & Bäckström (1996) and Zone NSB 17 of King (1983).

Description: This assemblage contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum* occurs frequently throughout. Other important species include *H. orbiculare*, *E. ustulatum*, *B. tenerrima*, *E. asklundi* and *C. teretis* (Fig. 5a). Mollusc fragments are also common.

Remarks: The foraminifera in this assemblage are characteristic Pliocene–Pleistocene taxa. All the recorded species are extant. Knudsen & Asbjörndóttir (1991) describe a *C. teretis – E. excavatum* assemblage Zone (Jo 7) in Lower Pleistocene sediments of borehole 30/13-2x.

CIBICIDES GROSSUS ASSEMBLAGE

Designation: CE-DB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. grossus*. The base is marked by the highest occurrence of *Monspeliensina pseudotepida*.

Depth range: 530.3–823 m.

Material: Two conventional core samples at 531.9 and 535.4 m, nine sidewall cores and 15 ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Subzones NSB 15a and b of King (1989), Zone Jo 8 of Knudsen & Asbjörndóttir (1991), *C. grossus* Zone of Pedersen (1995) and Zone NSR 12B of Gradstein & Bäckström (1996).

Description: This interval contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum* and *C. teretis* occur most frequently. Other important species include *Bulimina marginata*, *C. grossus*, *H. orbiculare*, *N. affine*, *B. tenerrima*, *E. albiumbilicatum* and *Elphidiella hannai* (lower part) (Fig. 5a).

Remarks: King (1989), Gradstein & Bäckström (1996), Knudsen & Asbjörndóttir (1991) and Pedersen (1995) place the Pliocene/Pleistocene boundary at the highest occurrence of *C. grossus*. According to Knudsen & Asbjörndottir (1991) and Pedersen (1995), the age of the Pliocene/Pleistocene boundary is 2.3 m.y. based on Zagwijn (1985, 1989). However, King (1989) gives this boundary an age of 1.61 m.y. based on Berggren et al. (1985). A calibration of the *C. grossus* Zone (CE-DB) in well 2/4-C-11 based on a comparison with the planktonic foraminiferal zones indicates that the top of the *C. grossus* Zone is close to ca. 1.6 m.y. in this area. However, the core at 527.3–535.7 m shows reverse polarity, indicating deposition slightly before or slightly after the Olduvai normal polarity Subchron (1.66–1.88 Ma).

MONSPELIENSINA PSEUDOTEPIDA ASSEMBLAGE

Designation: CE-EB.

Definition: The top of the assemblage is placed at the highest occurrences of *M. pseudotepida*. The base is defined by the highest occurrence of *Cibicidoides limbatosuturalis*.

Depth range: 823–932.7 m.

Material: Two sidewall cores and four ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Subzone NSB 14b of King (1989), Zone NSR 12A of Gradstein & Bäckström (1996) and Zone Jo 10 of Knudsen & Asbjörndóttir (1991).

Description: This assemblage contains a rich benthonic fauna of mainly calcareous foraminifera. A few agglutinated taxa are also present. *C. teretis*, *B. marginata*, *M. pseudotepida* and *E. excavatum* are common. Other characteristic species include *N. affine* and *B. tenerrima* (Fig. 5a).

Remarks: A *M. pseudotepida* Subzone (NSB 14b) is described from lower part of Upper Pliocene in the North Sea (King 1989).

C. grossus and *E. hannai* are also recorded in assemblage CE-EB in ditch cutting samples. These forms are not recorded in sidewall cores, indicating that the specimens are caved.

CIBICIDOIDES LIMBATOSUTURALIS ASSEMBLAGE

Designation: CE-FB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. limbatosuturalis*. The base is marked by the highest occurrence of *Uvigerina venusta saxonica*.

Depth range: 932.7–1015 m.

Material: Two sidewall cores and four ditch cutting samples.

Age: Early to Late Pliocene.

Lithostratigraphic unit: Nordland group.

Correlation: Subzone NSB 14a of King (1989).

Description: This interval is characterized by a rich benthonic fauna of mainly calcareous foraminifera. Taxa are slightly more numerous in this assemblage than in the immediately overlying section. *M. pseudotepida* and *Cassidulina pliocarinata* occur frequently throughout. Other important species include *C. limbatosuturalis*, *N. affine*, *Pullenia bulloides*, *B. marginata*, *Sigmoilopsis celata* (agglutinated), *Bolivina* cf. *robusta*, *Globocassidulina subglobosa* and *E. excavatum* (Fig. 5a).

Remarks: King (1989) describes a *C. limbatosuturalis* Subzone (NSB 14a) from Lower to Upper Pliocene in the North Sea. According to King (1989), the lower part of Subzone NSB 14a is close to the Lower/Upper Pliocene boundary.

E. excavatum is recorded in ditch cutting samples, not in sidewall cores, indicating that this species is caved.

UVIGERINA VENUSTA SAXONICA ASSEMBLAGE

Designation: CE-GB.

Definition: The top of the assemblage is defined by the highest occurrence of *U. venusta saxonica*. The base is indicated by the highest occurrence of *Glomospira charoides*.

Depth range: 1015–1426.5 m.

Material: Three conventional core samples from 1162.6–1166 m, nine sidewall cores and 20 ditch cutting samples.

Age: Late Miocene to Early Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone NSB 13 of King (1989).

Description: This interval contains a very rich benthonic fauna of mainly calcareous foraminifera. Taxa are even more numerous in this assemblage than in the immediately overlying assemblage. *U. venusta saxonica*, *Florilus boueanus*, *C. pliocarinata* and *C. limbatosuturalis* occur most frequently. Other important species include *Bolivina* cf. *robusta*, *G. subglobosa*, *B. marginata*, *A. fluens*, *P. bulloides* and *N. affine* (Figs. 5a, b).

Remarks: An *U. venusta saxonica* Zone (NSB 13) is described from Upper Miocene to Lower Pliocene deposits in the North Sea (King 1989).

GLOMOSPIRA CHAROIDES ASSEMBLAGE

Designation: CE-HB.

Definition: The top of the assemblage is defined by the highest occurrence of *G. charoides*. The base is indicated by the highest consistent occurrence of *Bulimina elongata*.

Depth range: 1426.5–1664.7 m.

Material: Three conventional core samples from 1559.6–1563.2 m, four sidewall cores and 14 ditch cutting samples.

Age: Middle to Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone NSA 12 of King (1989) and probably Zone NSR 9B of Gradstein & Bäckström (1996).

In-place assemblage composition: There are significantly fewer foraminifera in this interval than in the overlying assemblages. Both agglutinated and calcareous taxa are present, but the agglutinated species are dominant. *G. charoides* is the most common agglutinated species. Other important agglutinated taxa include *Bathysiphon* ? sp. A (King 1989), *Bathysiphon* spp., *Trochammina* spp., *Cyclammina placenta*, *Haplophragmoides* spp. and *Ammodiscus* sp. *M. pseudotepida*, *Eponides umbonatus*, *Sphaeroidina bulloides*, *N. affine* and *P. bulloides* are the dominant calcareous taxa. In addition, sponge spicules (rod-shaped and *Geodia* sp.) occur in this assemblage (Fig. 5b).

Reworked assemblage composition: Valvulineria petrolei, *Trifarina gracilis*, *Gyroidina soldanii girardana*, *Elphidium antoninum* and *Turrilina alsatica* are recorded from the lower part of the interval. These taxa have been derived from Upper Oligocene to Lower Miocene sediments.

Remarks: King (1989) describes an unnamed Zone (NSA 12), which is the youngest significant assemblage with agglutinated foraminifera in the North Sea, characterized mainly by long-ranging species. This zone is known from Middle to Upper Miocene sediments. The base of assemblage CE-HB coincides with a regional seismic reflector.

BULIMINA ELONGATA ASSEMBLAGE

Designation: CE-IB.

Definition: The top of the assemblage is taken at the highest occurrence of *B. elongata*. The base is marked by the highest occurrence of *Uvigerina tenuipustulata*.

Depth range: 1664.7–1783.1 m.

Material: Seven conventional core samples from 1710.7–1724.9 m, three sidewall cores and six ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Probably Subzone NSB 12a and Zone NSB 11 of King (1989) and probably Zone NSR 8B of Gradstein & Bäckström (1996).

Description: There are even fewer foraminifera in this assemblage than in the immediately overlying assemblage. Both calcareous and agglutinated taxa are present. Calcareous taxa are somewhat more numerous. *B. elongata* is most common. Other characteristic species include *P. bulloides*, *Valvulineria mexicana grammensis*, *Stainforthia schreibersina*, *Virgulinella pertusa*, *Bolivina dilatata*, *T. alsatica*, *Alabamina tangentialis* and *Uvigerina semiornata saprophila*. *C. placenta*, *G. charoides*, *Trochammina* sp., *Bathysiphon* sp. and *Reophax* sp. are the most important agglutinated taxa (Fig. 5b).

Remarks: According to King (1989), the LAD of *B. elongata* is observed somewhat above the Middle/Upper Miocene boundary, but this form is common only in the Middle Miocene. *U. semiornata saprophila* (recorded at one level in the middle part of the unit), *B. dilatata*, *A. tangentialis*, *S. schreibersiana* and *V. pertusa* are known from the lower part of Middle Miocene (King 1989; Doppert 1980). The index fossils of Subzones NSB 12a and b (middle part of the Middle Miocene), designated by King (1989), are missing in this interval. This indicates that this unit only represents sediments of the lower part of the Middle Miocene and that there is a hiatus between this unit and the overlying unit. *T. alsatica* is probably reworked from Oligocene deposits.

UVIGERINA TENUIPUSTULATA ASSEMBLAGE

Designation: CE-JB.

Definition: The top of the assemblage is defined by the highest occurrence of *U. tenuipustulata*. The base is marked by the highest occurrence of *Ammodiscus* sp. A (King 1989).

Depth range: 1783.1–1856.7 m.

Material: The assemblage has been observed in two sidewall cores and four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSB 10 of King (1989), lower part of Zone NSR 8B of Gradstein & Bäckström (1996) and Zone FD of Doppert (1980).

Description: In this interval, foraminifera are as sparse as in the immediately overlying assemblage. Both agglutinated and calcareous taxa are present. Calcareous forms are most important in the upper part of the assemblage, and agglutinated forms are most common in the lower part. *B. elongata* is the most frequent calcareous form. Other characteristic calcareous taxa include *U. tenuipustulata*, *A.*

querichi staeschei, *V. petrolei* and *Loxostomum sinuosum*. *G. charoides*, *Bathysiphon* spp., *Martinottiella bradyana*, *Haplohragmoides* spp. and *Ammodiscus* sp. are the most important agglutinated taxa (Fig. 5b).

Remarks: King (1989) defined an *U. tenuipustulata* Zone (NSB 10) from the upper part of the Lower Miocene in the North Sea. According to King (1989), the LAD of *A. staeschei* is in the lower part of the Middle Miocene. In well 2/4-C-11, *A. querichi staeschei* does not reach higher than *U. tenuipustulata*. This may indicate that *A. querichi staeschei* is caved from the overlying interval, without being recorded there, or that the LAD of this form is different in well 2/4-C-11 than in the zonation of King (1989). The base of the CE-JB assemblage coincides with a regional seismic reflector.

AMMODISCUS SP. A – *CYCLAMMINA PLACENTA* ASSEMBLAGE

Designation: CE-KB.

Definition: The top of the assemblage is taken at the highest occurrence of *Ammodiscus* sp. A. The base is marked by the highest occurrence of *Spirosigmoilinella compressa*, which is synonymous with *Spirosigmoilinella* sp. A of King (1989) according to S. Bäckström and F. Gradstein (personal communication 1998).

Depth range: 1856.7–1975 m.

Material: One sidewall core and five ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Probably lower part of Zone NSA 11 of King (1989) and lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This assemblage contains a rich benthonic fauna of agglutinated foraminifera. *G. charoides* is most common. Other important taxa include *Ammodiscus* sp. A, *Ammodiscus* spp., *C. placenta*, *Reticulophragmium rotundidorsatum*, *Haplophragmoides* spp., *Bathysiphon* spp., *Haplophragmoides walteri* and *Bathysiphon eocenicus* (Fig. 5b).

Remarks: According to King (1989), the LAD of *Ammodiscus* sp. A in the lower part of the Lower Miocene is slightly above the LAD of *S. compressa*. This is also the case in well 2/4-C-11.

SPIROSIGMOILINELLA COMPRESSA ASSEMBLAGE

Designation: CE-LB.

Definition: The top of the assemblage is taken at the highest occurrence of *S. compressa*. The base is marked the highest occurrence of *Annectina biedai* (Gradstein & Kaminski 1997), which is synonymous with *Ammodiscus* sp. B of King (1989) according to S. Bäckström and F. Gradstein (personal communication 1998).

Depth range: 1975–2039.1 m.

Material: Three ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSA 10 of King (1989) and lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: A rich foraminiferal fauna of agglutinated species is found in this unit. *S. compressa* appears frequently throughout the entire unit. Other important taxa include *C. placenta*, *H. walteri*, *B. eocenicus*, *B. nodosariformis* and *Recurvoides* spp. (Fig. 5b).

Remarks: King (1989) describes a *Spirosigmoilinella* sp. A (synonymous with *S. compressa*) Zone (NSA 10) in Lower Miocene deposits in the North Sea.

ANNECTINA BIEDAI ASSEMBLAGE

Designation: CE-MB.

Definition: The top of the assemblage is taken at the highest occurrence of *A. biedai*. The base of the assemblage is undefined.

Depth range: 2039.1–2368.3 m (lowermost studied sample).

Material: Two conventional core samples at 2298.7 and 2303.1 m, one sidewall core and 17 ditch cutting samples.

Age: Late Oligocene to Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSA 9 and probably the lower part of Zone NSR 8A of King (1989), and the upper part of Zone NSR 7A of Gradstein & Bäckström (1996).

Description: This interval contains a rich benthonic fauna of mainly agglutinated foraminifera. *S. compressa*, *B. eocenicus* and *C. placenta* all occur frequently throughout. Other important species include *Ammodiscus* sp. A, *A. biedai*, *R. rotundidorsatum* and *Rhabdammina* (Fig. 5b).

The calcareous forms have sporadic occurrences with the following taxa present: *Plectofrondicularia seminuda*, *Cibicides sulzensis* and *Rolfina arnei*. According to Laursen (1994), *R. arnei* is synonymous with *Rotalia* sp. 1 of Larsen & Dinesen (1959) and *Glabratella* ? sp. A of King (1989).

Remarks: King (1989) described an *Ammodiscus* sp. B (synonymous with *A. biedai*) Zone (NSA 9) from Upper Oligocene to Lower Miocene sediments in the North Sea. *P. seminuda* is known from the Lower Oligocene to the Lower Miocene in the North Sea (King 1989). *C. sulzensis* is described from Oligocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986). *R. arnei* is recorded from Upper Oligocene to Lower Miocene deposits in Denmark (Larsen & Dinesen 1959) and in the North Sea (King 1989; Laursen 1994).

Planktonic assemblages

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) ASSEMBLAGE

Designation: CE-AP.

Definition: The top of the assemblage extends to the uppermost investigated sample (190 m). The base of the assemblage is marked by the highest consistent occurrence of *N. pachyderma* (dextral).

Depth range: 190–568 m.

Material: One conventional core sample at 374.7 m and three conventional core samples from 528.2–535.4 m, 18 sidewall cores and nine ditch cutting samples.

Age: Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. pachyderma (sinistral) Zone of Weaver & Clement (1986), *N. pachyderma* (sinistral) Zone of Spiegler & Jansen (1989) and Subzone NSP 16b of King (1989).

Description: Very few planktonic foraminifera are recorded from this unit. Sporadic occurrences of *N. pachyderma* (sinistral), *N. pachyderma* (dextral) (in one interval) and the reworked Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. are the only representatives (Fig. 5a).

Remarks: A *N. pachyderma* (sinistral) Zone is described by Weaver & Clement (1986) from the North Atlantic and by Spiegler & Jansen (1989) from the Vøring Plateau in sediments younger than 1.7 Ma. At these open ocean sites, an encrusted variety of the sinistrally coiled *N. pachyderma* dominates over an unencrusted form. The encrusted variety occurs only very sporadically in older sediments, but the unencrusted variety also occurs in older Pliocene deposits. In well 2/4-C-11, only *N. pachyderma* (sinistral, unencrusted) is recorded. The reason for this is not that the deposits are older than 1.7 Ma, but probably that the specimens registered in this interval are small juvenile forms, and that the larger encrusted forms have not reached this shallow marine area.

NEOGLOBOQUADRINA PACHYDERMA (DEXTRAL) ASSEMBLAGE

Designation: CE-BP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *N. pachyderma* (dextral). The base is placed at the highest consistent occurrence of *Globigerina bulloides*.

Depth range: 568–914.4 m.

Material: Seven sidewall cores and 16 ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. pachyderma (dextral) Zone of Weaver (1987), Weaver & Clement (1987) and Spiegler & Jansen (1989) and Subzone NSP 16a of King (1989).

Description: Although planktonic foraminifera are sparse in this interval, they are significantly more common than in the immediately overlying section. *N. pachyderma* (dextral) are dominant. Other species include *N. pachyderma* (sinistral, unencrusted), *G. bulloides* and *Turborotalia quinqueloba* (Fig. 5a).

Remarks: A *N. pachyderma* (dextral) Zone is described by Weaver (1987) and Weaver & Clement (1987) from the North Atlantic (DSDP Leg 94) and by Spiegler & Jansen (1989) from the Vøring Plateau in Upper Pliocene deposits. On the Vøring Plateau the zone is accurately dated to 1.84–1.7 Ma.

GLOBIGERINA BULLOIDES ASSEMBLAGE

Designation: CE-CP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *G. bulloides*. The base is marked by the highest occurrence of *Neogloboquadrina atlantica* (sinistral).

Depth range: 914.4–951 m.

Material: Two ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Globigerina bulloides Zone of Weaver & Clement (1986).

Description: Planktonic foraminifera are significantly more common in this assemblage than in the immediately overlying section. *G. bulloides* and *T. quinqueloba* occur most frequently. Other species include *N. pachyderma* (sinistral, unencrested) and *N. pachyderma* (dextral) (Fig. 5a).

Remarks: A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Upper Pliocene deposits and is accurately dated to 2.3–2.1 Ma (Weaver & Clement 1986).

GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: CE-DP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (sinistral). The base is taken at the highest occurrence of *N. atlantica* (dextral).

Depth range: 951–1115.6 m.

Material: Three sidewall cores and eight ditch cutting samples.

Age: Early to Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: N. atlantica (sinistral) Zone of Weaver & Clement (1986), *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989) and Subzone NSP 15d of King (1989).

Description: This interval contains a rich planktonic foraminiferal fauna. *G. bulloides* and *N. atlantica* (sinistral) occur frequently throughout the unit. *N. pachyderma* (sinistral, unencrusted) is recorded from the upper part of the interval (Fig. 5a).

Remarks: A *N. atlantica* (sinistral) Zone is described from the North Atlantic in Upper Pliocene deposits (Weaver & Clement 1986), and from the Vøring Plateau in Lower to Upper Pliocene deposits (Spiegler & Jansen 1989). The LAD of *N. atlantica* (sinistral) is, in both areas, ca. 2.3 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). On the Vøring Plateau, there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this. *G. bulloides* is also found in the warmest interglacials of the last 1 Ma, however (Kellogg 1977).

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) ASSEMBLAGE

Designation: CE-EP.

Definition: The top of the assemblage is defined by the highest occurrence of *N. atlantica* (dextral). The base is characterized by the highest occurrence of *Neogloboquadrina acostaensis*.

Depth range: 1115.6–1197.9 m.

Material: Three conventional core samples from 1162.6–1166 m and four ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989) and upper part of *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987).

Description: This assemblage contains a rich planktonic foraminiferal fauna, where *G. bulloides* and *N. atlantica* (sinistral) are most common. *N. atlantica* (dextral) also occurs throughout (Fig. 5a).

Remarks: Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau. Weaver (1987) and Weaver & Clement (1987) report a *N. atlantica* (dextral)/*N. acostaensis* Zone from Upper Miocene sediments in the North Atlantic (DSDP Leg 94).

NEOGLOBOQUADRINA ACOSTAENSIS ASSEMBLAGE

Designation: CE-FP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. acostaensis*. The base is taken at the highest occurrence of *Bolboforma metzmacheri*.

Depth range: 1197.9–1554.5 m.

Material: Ten sidewall cores and 18 ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *N. acostaensis* Zone of Spiegler & Jansen (1989), lower part of *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987) and Subzone NSP 15a of King (1989).

Description: The upper part of this assemblage contains a moderately rich planktonic foraminiferal fauna. In the lower part planktonic foraminifera are much less frequent. Pyritized diatoms occur sporadically throughout the interval. *G. bulloides*, *N. atlantica* (sinistral) and *N. acostaensis* occur most frequently. Other species include *Globorotalia puncticulata*, *Neogloboquadrina praehumerosa* and *N. atlantica* (dextral) (Figs. 5a, b).

Remarks: *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989; Müller & Spiegler 1993). Weaver (1987) and Weaver & Clement (1987) describe a *N. atlantica* (dextral)/*N. acostaensis* Zone from the Upper Miocene in the North Atlantic. King (1989) describes a *N. acostaensis* Zone above a *B. metzmacheri* Zone from the Upper Miocene in the North Sea.

BOLBOFORMA METZMACHERI ASSEMBLAGE

Designation: CE-GP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. metzmacheri*. The base is marked by the highest occurrence of *Bolboforma fragori* and *B. subfragori*.

Depth range: 1554.5–1600.2 m.

Material: Three conventional core samples from 1559.6–1563.2 m, one sidewall core and three ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *B. metzmacheri* Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), Zone NSR 10 of Gradstein & Bäckström (1996) and Subzone NSP 14b of King (1983).

Description: This assemblage contains a rich planktonic fauna of foraminifera and *Bolboforma*. The most important foraminfera are *N. atlantica* (sinistral) and *N. atlantica* (dextral). *N. continuosa* and *Orbulina universa* are also recorded. *B. laevis* is the most common *Bolboforma*. *B. metzmacheri* is also recorded (Fig. 5b).

Remarks: The stratigraphically important planktonic foraminifera registered in this interval are mentioned above. *B. metzmacheri* is described from deposits with an age of 9.2–7.9 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

BOLBOFORMA FRAGORI – BOLBOFORMA SUBFRAGORI ASSEMBLAGE

Designation: CE-HP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. fragori* and *B. subfragori*. The base is marked by the highest occurrence of *Globigerina praebulloides*.

Depth range: 1600.2–1664.7 m.

Material: One sidewall core and four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *B. fragori*/*B. subfragori* Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993) and Subzone NSP 14a of King (1983).

Description: The upper part of this interval contains a moderately rich planktonic fauna, while its lower part contains a sparse planktonic assemblage. *Bolboforma* are dominant, with subordinate foraminifera. *B. clodiusi* and *B. subfragori* are the most common *Bolboforma* species. *B. fragori*, *B. pseudohystrix* and one specimen of *B. reticulata* are also recorded. *N. atlantica* (dextral) is the most important foraminifer. Other foraminifera include *N. atlantica* (sinistral), *N. acostaensis*, *N. pachyderma* (sinistral, unencrusted) and the *Globorotalia zealandica*/*G. praescitula* group (Fig. 5b).

Remarks: The known stratigraphic ranges of the most important planktonic foraminifera are discussed above under the descriptions of assemblages CE-EP and CE-FP. A *B. fragori*/*B. subfragori* Zone is described from deposits with an age of ca. 11.5–9.6 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

Poore (1979) describes *G. zealandica* and *G. praescitula* from Lower Miocene to lower Middle Miocene deposits of the North Atlantic (Leg 49). These foraminifera have probably been reworked from deposits which correspond to the immediately underlying assemblage. The base of assemblage CE-HP coincides with a regional seismic reflector which represents a depositional hiatus.

GLOBIGERINA PRAEBULLOIDES – GLOBIGERINOIDES QUADRILOBATUS TRILOBA ASSEMBLAGE

Designation: CE-IP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. praebulloides*. The base is marked by the highest occurrence of *Globigerina ciperoensis*.

Depth range: 1664.7–1783.1 m.

Material: Seven conventional core samples from 1710.7–1724.9 m, three sidewall cores and six ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 12 of King (1983) and Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This assemblage contains a rich planktonic fauna of foraminifera and radiolaria, where *G. praebulloides* is the most common foraminifer. Other species include *G. quadrilobatus triloba*, *G. zealandica/G. praescitula* and *Sphaeroidinellopsis disjuncta* (Fig. 5b).

Remarks: *G. quadrilobatus triloba* is described from Middle Miocene deposits in the North Sea (King 1983). *G. zealandica/G. praescitula* are described from the Lower Miocene to lower Middle Miocene in the North Atlantic (Leg 49) (Poore 1979) and in the North Sea (King 1983). *G. praebulloides* is known from Oligocene to lower Upper Miocene (common in Middle Miocene) deposits in the North Atlantic (Poore 1979) and from Oligocene to lower Middle Miocene deposits in the North Sea (Gradstein & Bäckström 1996). Poore (1979) suggests that a clear separation of *G. praebulloides* and *G. bulloides* may be difficult in extra-tropical regions. This is supported by the present study. *S. disjuncta* is known from Lower to Middle Miocene sediments in the North Sea (Gradstein & Bäckström 1996).

The *Bolboforma badenensis* and *B. reticulata* Zones known from the North Atlantic (Spiegler & Müller 1992) and the *B. badenensis/B. reticulata* Zone known from the Vøring Plateau (Müller & Spiegler 1993) are not recorded in this well. These zones are recorded from deposits with an age of ca. 14–11.5 Ma (Spiegler & Müller 1992). This indicates that the CE-IP assemblage only represents sediments of the lower part of the Middle Miocene and that there is a hiatus between this unit and the overlying unit.

GLOBIGERINA CIPEROENCIS ASSEMBLAGE

Designation: CE-JP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. ciperoensis*. The base is marked by the lowest consistent occurrence of *G. ciperoensis*.

Depth range: 1783.1–1856.7 m.

Material: Two sidewall cores and four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This assemblage contains a rich planktonic fauna of foraminifera and radiolaria. *G. ciperoensis* and *Globigerina angustiumbilicata* are the most common foraminifera. Other characteristic species include *Globigerina woodi*, *G. praebulloides* and *G. quadrilobatus triloba* (Fig. 5b).

Remarks: G. ciperoensis is described from Upper Oligocene to Lower Miocene deposits in the North Atlantic (Poore 1979) and in the North Sea (Gradstein & Bäckström 1996). *G. woodi* is known from Upper Oligocene to Lower Pliocene sediments in the North Atlantic (Poore 1979). *G. angustiumbilicata* is recorded from Upper Oligocene to Lower Pliocene deposits (Kennet & Srinivasan 1983). This indicates an Early Miocene age for this interval, since Late Oligocene can be ruled out (see below).

UNDEFINED INTERVAL

Depth range: 1856.7–2167.1 m.

Material: One sidewall core and 14 ditch cutting samples.

Lithostratigraphic unit: Hordaland Group.

Description: This interval contains no planktonic fossils of stratigraphic importance. Only a few unidentified radiolaria and pyritized diatoms are recorded (Fig. 5b).

DIATOM SP. 4 ASSEMBLAGE

Designation: CE-KP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of Diatom sp. 4 (King 1983). The base is marked by the highest consistent occurrence of Diatom sp. 3 (King 1983).

Depth range: 2167.1–2203.7 m.

Material: One ditch cuttings sample.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Description: This interval contains a moderately rich flora of pyritized diatoms. The index fossils Diatom sp. 4 and Diatom sp. 5 (King 1983) are found in this flora (Fig. 5b).

Remarks: Diatom sp. 4 and Diatom sp. 5 are both known from Lower Miocene deposits in the North Sea (King 1983).

DIATOM SP. 3 ASSEMBLAGE

Designation: CE-LP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of Diatom sp. 3 (King 1983). The base of the assemblage is undefined.

Depth range: 2203.7–2368.3 m (lowermost studied sample).

Material: Two conventional core samples at 2298.7 and 2303.1 m, one sidewall core and nine ditch cutting samples.

Age: Late Oligocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSP 9c of King (1989).

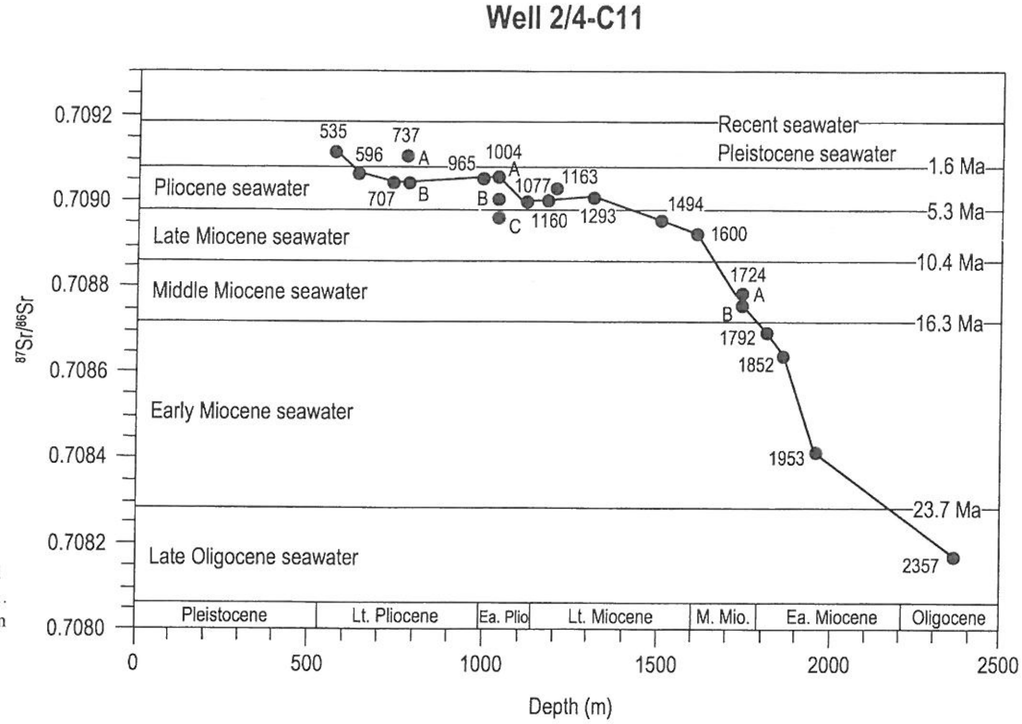

Fig. 6. Strontium isotope ratios plotted as a function of depth in well 2/4-C-11. Biostratigraphical datings are shown on the horizontal axis. The Sr isotope zonation is after Hodell et al. (1990). Chronology is after Berggren et al. (1985).

Description: This assemblage contains a moderately rich flora of pyritized diatoms. In this flora the index fossil Diatom sp. 3 is found. The assemblage also contains a few specimens of the following planktonic foraminiferal taxa: *G. ciperoensis*, *G. angustiumbilicata* and *G. praebulloides* (Fig. 5b).

Table 2. Strontium isotope data from well 2/4-C-11. All measurements refer to the international standard NBS 987 = 0.710240.

Depth (m)	Sample[1]	$^{87}Sr/^{86}Sr$	S.E.[2]	Age (m.y.)[3]	Comments[4]
535.4	BF	0.709105	± 15	1.4	Core, 8 bl.
596	BF	0.709068	± 11	2.0	SWC
707	BF	0.709047	± 11	2.5–4.5	SWC
737A	BF	0.709108	± 8	1.4	SWC
737B	BRY	0.709047	± 11	2.5–4.5	SWC
965	BF	0.709051	± 11	2.5–4.5	SWC
1004A	PF	0.709056	± 13	2.5–4.5	SWC
1004B	BF	0.708964	± 10	5.5	SWC
1004C	MOL	0.709003	± 8	5.0	SWC
1077	BF	0.708993	± 16	5.1	SWC
1160.7	BF	0.709007	± 10	5.0	Core
1163.4	BF	0.709022	± 12	4.8	Core
1293	BF	0.709004	± 19	5.0	SWC, 7 bl.
1494	BF	0.708951	± 10	5.5–8.0	SWC
1600	BOL	0.708928	± 28	8.0	Cuttings, 2bl.
1724A	MOL	0.708781	± 9	14.0	Core
1724B	BF	0.708756	± 13	14.8	Core
1792	PF	0.708697	± 18	16.9	SWC, 4bl.
1953	BF	0.708407	± 12	21.3	SWC
2357.3	BF	0.708165		25.6	SWC, 2bl.

[1] BF = bethonic foraminifera; PF = planktonic foraminifera; BRY = bryozoan fragment; MOL = mollusc fragment; BOL = Bolboforma.

[2] S.E. = standard error of the mean $(2\delta)\cdot 10^{-6}$.

[3] Age according to Hodell et al. (1990, 1992). Max. precision ± 0.5 Ma.

[4] Samples from: sidewall core (SWC), core or cuttings. bl. = blocks.

Remarks: Diatom sp. 3 is known from Upper Oligocene to lowermost Lower Miocene deposits in the North Sea (King 1989). Strontium isotope analyses indicate that an Early Miocene age can be ruled out.

Strontium isotope stratigraphy

Several papers describing the strontium (Sr) isotopic evolution of Cainozoic seawater were published during the 1980s (Burke et al. 1982; Koepnick et al. 1985; DePaolo & Ingram 1985; DePaolo 1986; Hess et al. 1986). Since these studies, segments of the seawater curve have been increasingly well documented, and for the Neogene portion of the curve, the most detailed record was presented by Hodell et al. (1990, 1991). As a consequence of these studies, Sr isotope stratigraphy is emerging as a powerful tool of dating and correlation of marine sediments. The method has particularly high potential for chronostratigraphical studies of post-Eocene sections.

In this study, we use Sr isotope stratigraphy to constrain better the ages for the Neogene section in well 2/4-C-11. In order to avoid problems with cavings, we used samples from sidewall cores and conventional cores (except for one ditch cutting sample). Most of the samples consisted of benthonic foraminifera, but at some levels we also used planktonic foraminifera, *Bolboforma*, *Bryozoa* and mollusc fragments. Furthermore, to avoid problems with reworking, we preferentially used taxa of well-documented stratigraphic range. Consequently, at some levels, relatively small samples were used.

A problem with obtaining Sr ages from foraminifera in siliciclastic basins is the common presence of impurities such as clay, pyrite, glauconite, etc. within the foraminiferal chambers. Addition of Sr from such materials leads to increased Sr isotopic ratios and hence younger ages, as demonstrated by Eidvin et al. (1993b). Careful cleaning of the foraminifera by washing and centrifugation processes normally does not help to resolve this problem. In this study, we overcame the problem by using a very weak acid (0.1 N HCl) to dissolve the foraminiferal tests. Such a weak acid is thought effective in minimizing addition of Sr from foreign matter. Stronger acids (e.g. 2.0 N HCl) dissolve the whole sample, and Sr from foreign matter thus increases the Sr isotopic ratios, resulting accordingly in younger ages.

The results from our study are presented in Table 2 and Fig. 6. The Sr ratios in Fig. 6 are plotted as a function of depth in the well. Biostratigraphic ages, as interpreted from the well data, are also shown along the horizontal axis. This illustration provides an adequate way of comparing results obtained from biostratigraphy and Sr isotope stratigraphy. Also shown in Fig. 6 are Sr isotopic zonations of Neogene seawater.

From Fig. 6 we can see a good correlation between biostratigraphy and Sr isotopic data. The uppermost sample (535 m) has a Sr isotopic composition that gives an Early Pleistocene age (ca. 1.4 Ma), whereas the sample from 596 m gives a Late Pliocene age (ca. 2.0 Ma). Assuming a constant sedimentation rate, these two results indicate the Upper Pliocene/Pleistocene boundary (ca. 1.6 Ma) to be at about 560 m, which is close to the biostratigraphic placing of this boundary (ca. 530 m).

The Sr values are then essentially stable from 596–1004 m, and correspond to deposition within the 2.5–4.5 m.y. time span, a period with little changes in seawater Sr composition (Hodell et al. 1990, 1991). These ages are also in good agreement with the biostratigraphic interpretation.

Between depths of 1004 and 1077 m, there is a small, but clear drop in the Sr isotopic ratio, and from 1077 to 1293 m we again measure stable Sr ratios. The isotopic composition at 1077 m corresponds to an age of 5.1 Ma, which suggests that the drop in Sr ratio corresponds to the time period 4.5–5.5 m.y., in which seawater Sr isotopic composition changed rapidly (Hodell et al. 1990, 1991).

Our data (from 596–1293 m) apparently mirror the two Sr isotopic plateaus (2.5–4.5 and 5.5–9.0 m.y.) published by Hodell et al. (1989, 1991). The isotopic difference we measure between the plateaus is, however, only half of that measured by Hodell et al. (1990, 1991). As the biostratigraphic data for samples at 1160, 1163 and 1293 m point to Late Miocene ages, we believe therefore that our Sr values for this lower plateau are slightly elevated. This could be explained by slight Sr contamination, or the values could reflect the uppermost level of uncertainty of the isotopic analyses.

The sample at 1600.2 m is the only one taken from ditch cuttings. It consists of specimens of the index fossils *Bolboforma subfragori*, and is taken from the top of the CE-HP assemblage. The top of the equivalent assemblage in the North Atlantic and in the Norwegian Sea is dated to 9.6 Ma (Spiegler & Müller 1992; Müller & Spiegler 1993). The Sr composition of this sample corresponds to deposition during the Late Miocene period with stable Sr seawater composition (5.5–9 m.y.). Because of the precise biostratigraphic dating for this sample, we suggest that the oldest age (ca. 9.0 Ma) is most correct.

Below 1600 m the samples show distinctly decreasing Sr signatures with depth, yielding ages between 14 and 25 Ma. Through this interval, Sr isotope stratigraphy has extremely good resolution. At 1724 m two samples were analysed: a mollusc fragment (sample A) gave an age of 14.0 Ma, whereas benthonic foraminifera (sample B) gave an age of 14.8 Ma. The isotopic difference between these two samples falls within the resolution of the method (±0.000030).

Samples at 1792, 1852 and 1953 m all yield Early Miocene ages, viz. 16.9, 17.8 and 21.3 Ma. These ages support the biostratigraphic datings in this interval. The deepest sample (2357 m) was very small, and was therefore treated manually in the mass spectrometer. The sparse amount of Sr gave 20 stable measurements corresponding to a Late Oligocene age of 25.6 Ma. This age is in good agreement with the biostratigraphic data.

Lithology and lithostratigraphy

Upper Oligocene and Middle Miocene (Hordaland and Nordland Groups)

This interval belongs to the Hordaland and Nordland Groups after Isaksen & Tonstad (1989). Studies of the petrophysical logs, the sidewall core samples and the ditch cutting samples show that this section contains mostly fine-grained material. Mostly clay is found in the samples, but small proportions of silt and fine-grained sand are also recorded. The conventional cores at 2297–2305.2 m (Upper Oligocene) and 1710.5–1725.5 m (Middle Miocene) contain mainly clay, but throughout the cores there are several thin beds with silt and fine-grained sand. These beds are probably distal turbidites.

Upper Miocene and Lower Pliocene (Nordland Group)

This section also contains mostly clay. The conventional cores at 1556.9–1563.2 m and 1160.7–1166.2 m (Upper Miocene) both consist of homogeneous clay-rich material.

Upper Pliocene and Pleistocene (Nordland Group)

In the lower part of the Pleistocene and the Upper Pliocene sections, the petrophysical logs indicate fine-grained deposits. The drill cuttings, sidewall cores and conventional cores from this section all contain a clay-rich diamicton with small proportions of sand, silt and pebbles. The pebbles, of both sedimentary and crystalline lithology, are interpreted as ice-rafted material and are found down to 900 m.

Petrophysical logs show that the uppermost ca. 300 m of the well contains thick sand beds with a fine-grained interval in between. The few sidewall cores from this unit contain mostly clay. These deposits are interpreted as glacial and glaciofluvial sediments.

The glaciomarine sediments of the Vøring Plateau have been the subjects of studies by Jansen & Sjøholm (1991) and Fronval & Jansen (1996). These investigations show traces of ice-rafted material in sediments as old as nearly 12 Ma. The frequency of such ice-rafted material increases during the period of 6.5–5.5 Ma, which correlates with the Messinian Stage. The frequency of ice-rafted material remains relatively low between 5.5 Ma and 2.6 Ma, but the great increase in the supply of such material after about 2.6 Ma reflects the marked expansion of northern European glaciers (Fig. 8). Shelf deposits from the last period contain large quantities of ice-rafted material further north in the North Sea (well 15/12–3, Eidvin & Riis 1992), on the Norwegian Sea continental shelf (Eidvin et al. 1998a) and in the Barents Sea (Eidvin et al. 1993a, 1998b).

The comparatively small quantities of ice-rafted detritus found in the Lower Pleistocene/Upper Pliocene section of well 2/4-C-11 indicate a smaller frequency of icebergs over this area than over the areas further north.

Paleoenvironments

Definition of bathymeteric zones are according to van Hinte (1978); inner neritic: 0–30 m, middle neritic: 30–100 m, outer neritic: 100–200 m and upper bathyal: 200–600 m.

Upper Oligocene and lower part of Lower Miocene

The fossil assemblage in this interval consists mainly of agglutinated foraminifera and pyritized diatoms. This foraminiferal fauna indicates deep water with dysoxic bottom conditions. A small proportion of benthonic calcareous foraminifera indicates short periods with better vertical water circulation and more oxygen at the sea bottom. The environment was probably upper bathyal during deposition of this section.

Upper part of Lower Miocene and lower part of Middle Miocene

This interval contains a rich planktonic foraminiferal fauna. A large proportion of planktonic foraminifera in coastal areas indicates open marine and fairly deep water conditions. The benthonic faunal component is dominated by calcareous forms, but agglutinated taxa are also recorded. At this time the sea level was probably at its highest during the Neogene, and during periods with high relative sea level there was better vertical water circulation in the Central Graben area (King 1989). Regional seismics show that this section thins out on the flanks of the Central Graben, but it is possible that the flank areas are covered with a thin transgressive section not detectable on seismic data. This section was probably also deposited in an upper bathyal environment.

Upper part of Middle Miocene and lower part of Upper Miocene

This interval shows a consistent occurrence of agglutinated foraminifera. The lower part of the interval is quite rich in planktonic taxa, but in its upper part only a few planktonic foraminifera occur. Such an agglutinated foraminiferal fauna, as found in this well in Middle/Upper Miocene deposits, is restricted to the deeper part of the Central Graben (King 1989). The scarcity of planktonic foraminifera in the upper part is probably due to dissolution of calcareous tests. According to King (1989), the sea level was somewhat lower during the Middle/Late Miocene than during than during the Early/Middle Miocene, causing less vertical water circulation in the deeper part of the Central Graben. The interval was probably deposited in an outer neritic to upper bathyal environment.

Upper part of Upper Miocene and Lower Pliocene

This section contains a rich planktonic fauna. The calcareous benthonic forms *N. affine* and *P. bulloides* occur consistently throughout the section. Today, *P. bulloides* and *N. affine* have a biogeographic range extending mainly along the upper part of the continental slope. *N. affine* is also common in outer shelf areas (Sejrup et al. 1981; Mackensen et al. 1985). Very few shallow water indicators belonging to the genus *Elphidium* are recorded. According to King (1989), the sea level was rising again during the late part of the Late Miocene and Early Pliocene. This section was probably deposited in an upper bathyal to outer neritic environment.

Lower part of Upper Pliocene

In most of the lower part of the Upper Pliocene planktonic foraminifera occur consistently (Fig. 5a). In this part, *N. affine* and *P. bulloides* also occur consistently. Shallow water indicators belonging to the genus *Elphidium* are scarce. The lower part of Upper Pliocene was probably deposited in an outer to middle neritic environment. A large proportion of boreal benthonic foraminifera, a small number of arctic forms and absence of glacigenic material all indicate transitional water conditions.

Upper part of Upper Pliocene

Planktonic foraminifera vary from scarce to common in this interval (Fig. 5a). The deep water form *N. affine* occurs consistently throughout most of the interval. Shallow water indicators belonging to the genus *Elphidium* are scarce to common. This interval was probably deposited in a middle neritic environment. Glacigenic material, a larger content of arctic benthonic foraminifera and a smaller content of

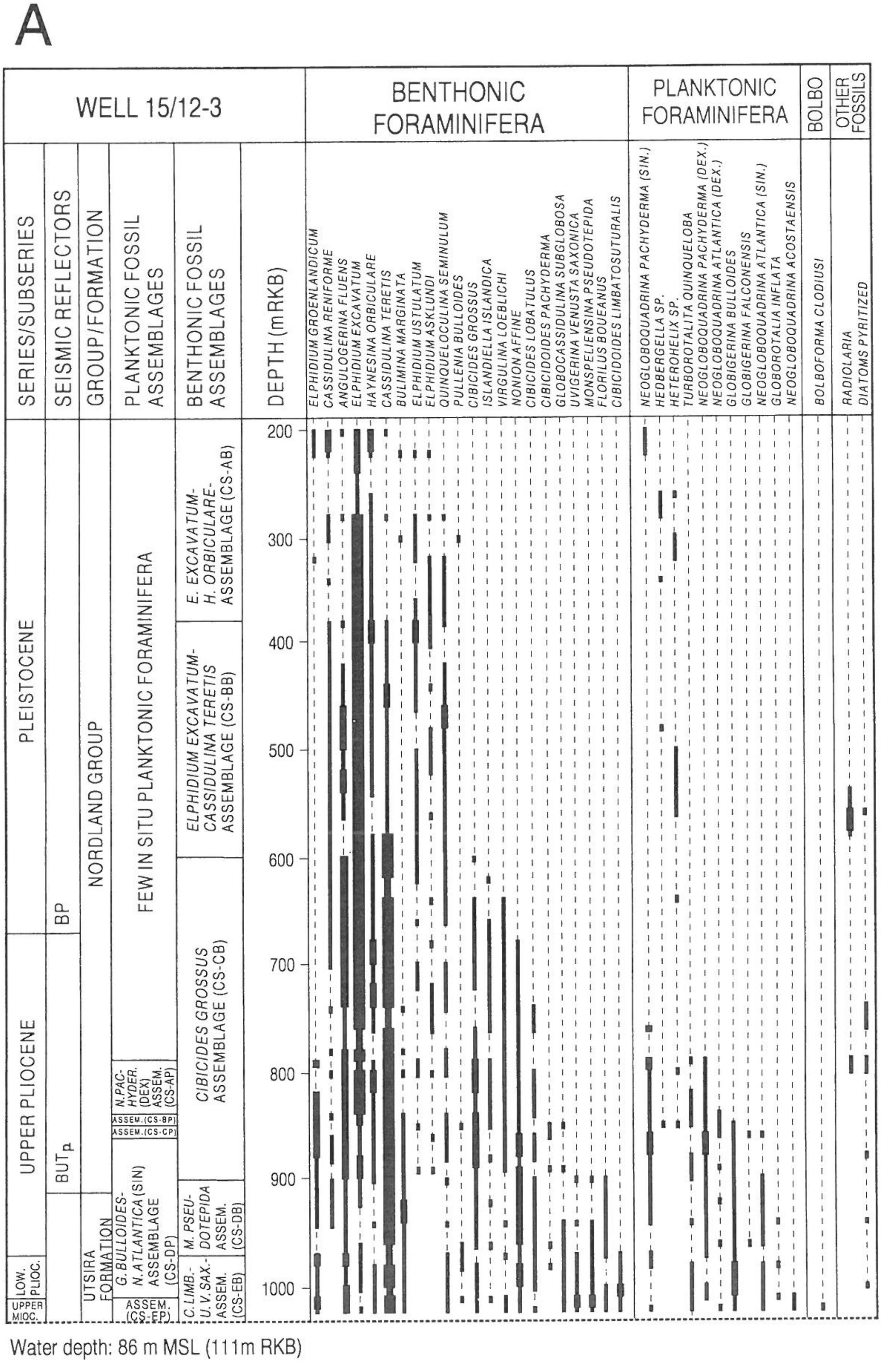

Fig. 7a. Range chart of the most important index fossils in the upper part of the investigated interval of well 15/12–3. BP = base Pleistocene, BUTp = base Upper Pliocene, mRKB = meters below rig floor, mMSL = meters below mean sea level.

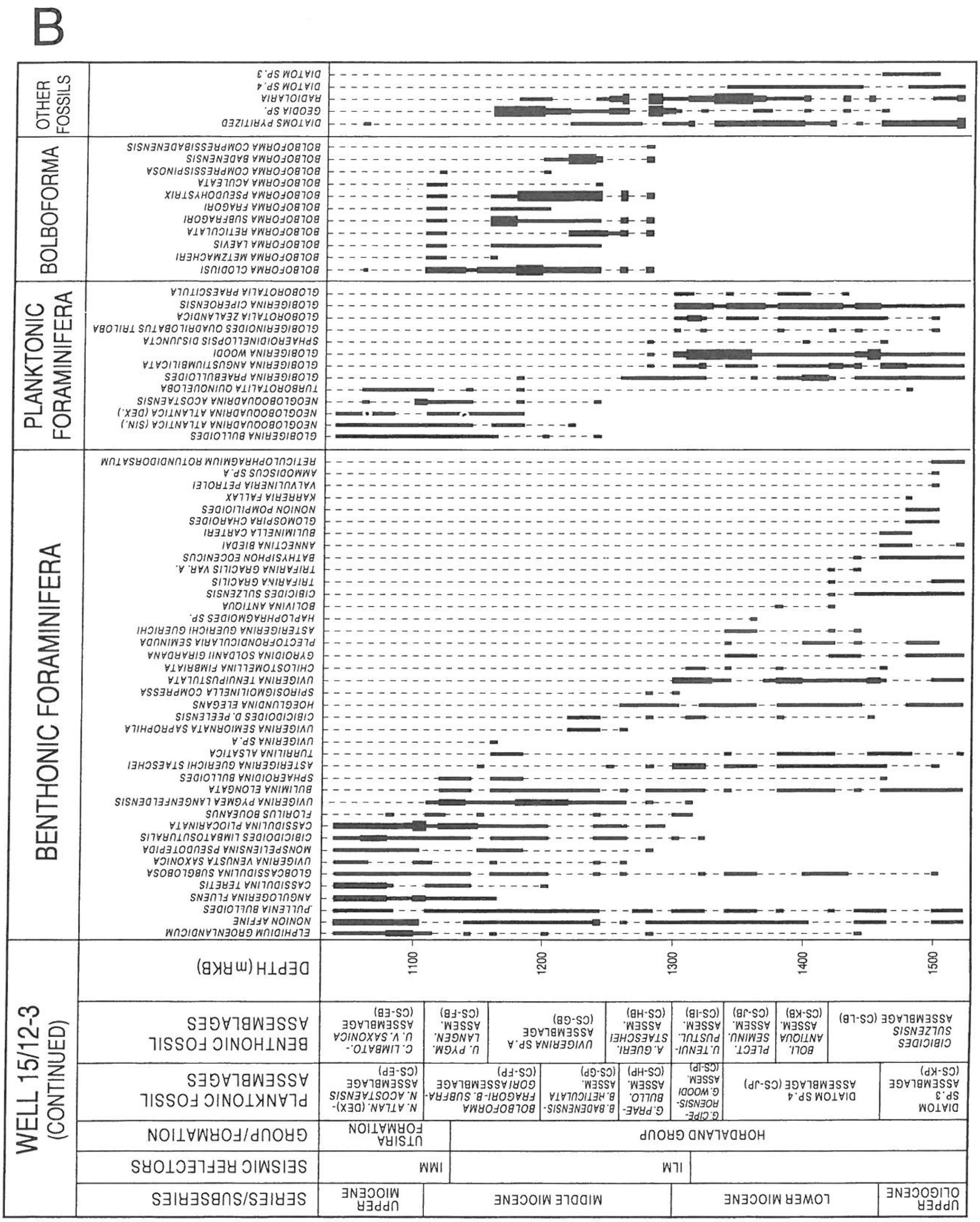

Fig. 7b. Range chart of the most important index fossils in the lower part of the investigated interval of well 15/12–3. IMM = intra-Middle Miocene, ILM = intra-Lower Miocene, mRKB = meters below rig floor.

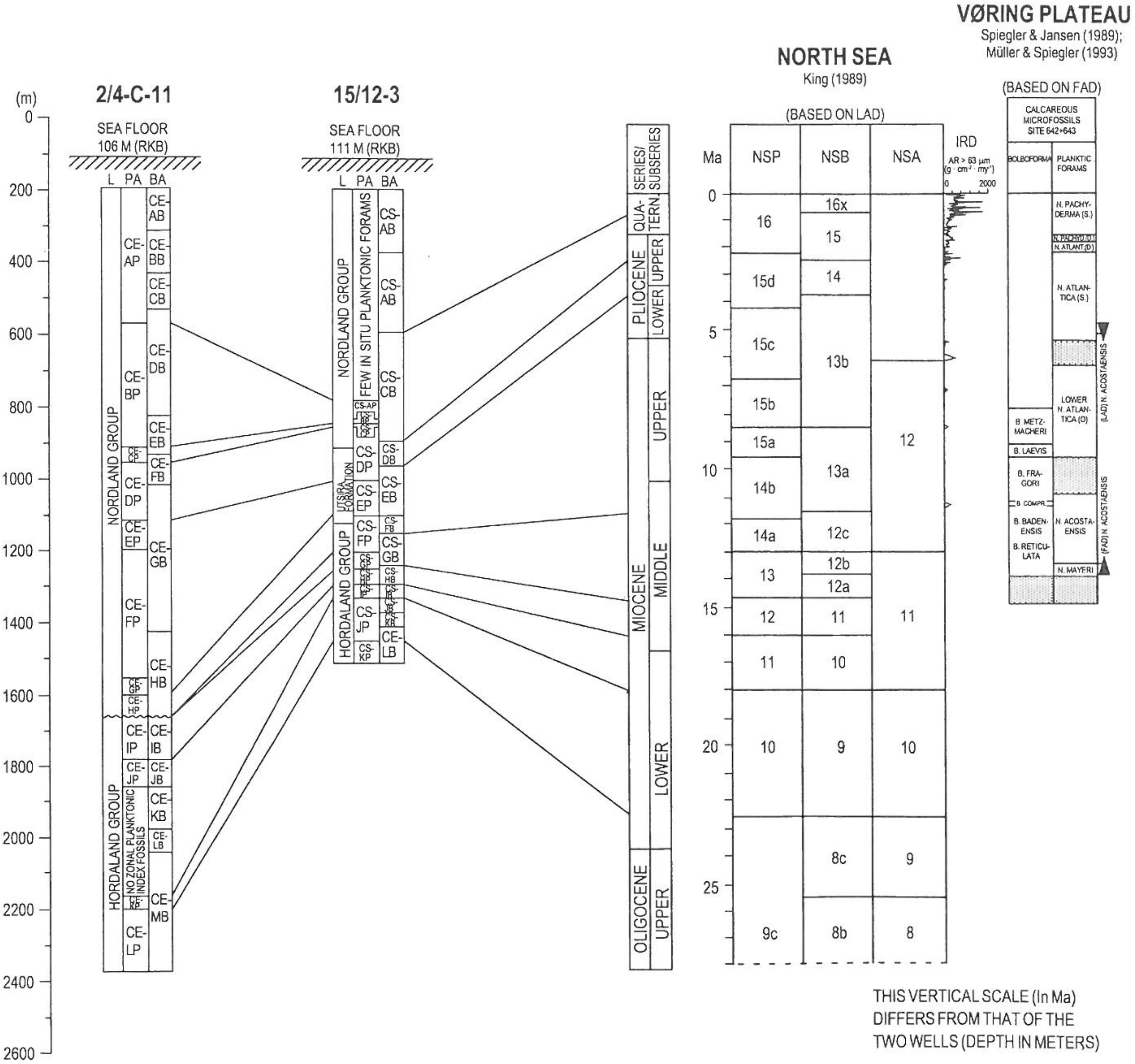

Fig. 8. Correlation of faunal assemblages between the wells studied, from the wells to King's (1989) North Sea fossil zonation and to the fossil zonation of ODP sites 642 and 643 on the Vøring Plateau (Spiegler & Jansen 1989; Müller & Spiegler 1993). The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). L = lithostratigraphic units, PA = planktonic fossil assemblages, BA = benthonic fossil assemblages, AR = accumulation rate, mRKB = meters below rig floor.

boreal forms all indicate considerably colder water than during the early Late Pliocene.

Pleistocene

The Pleistocene deposits contain very few planktonic foraminifera, indicating fairly shallow marine conditions. A shallow marine environment is also indicated by a large proportion of the benthonic foraminiferal genus *Elphidium*. Glacigenic material and a high content of arctic benthonic foraminifera indicate cold water conditions. The Pleistocene interval was probably deposited in an inner neritic environment.

Stratigraphy of well 15/12–3

Fossil assemblages

In this well, a system of 12 assemblages based on benthonic foraminifera (CS-AB to CS-LB) and 11 assemblages based on planktonic fossils (CS-AP to CS-KP) is

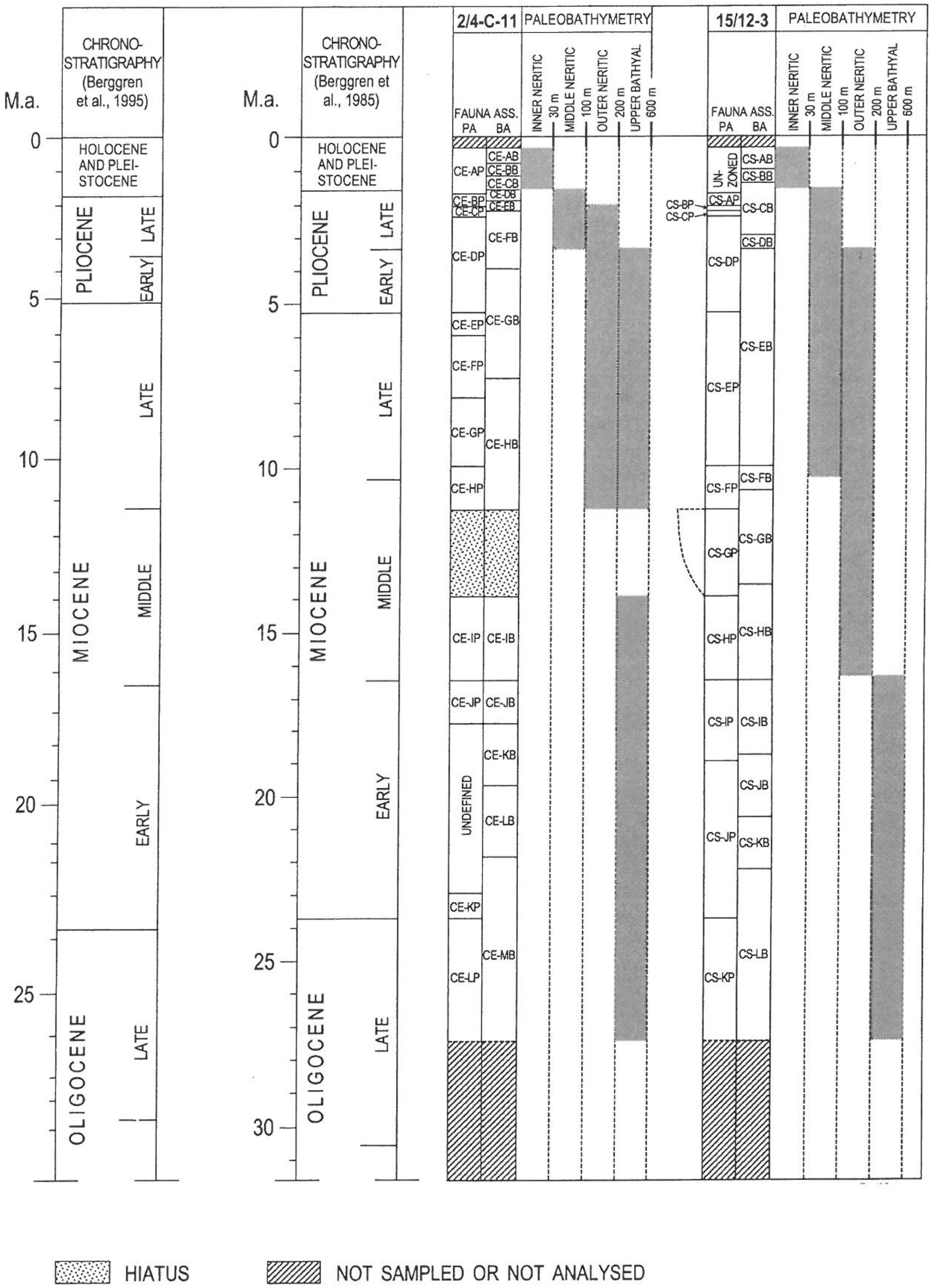

Fig. 9. Paleobathymetry and correlation of the faunal assemblages between the wells studied. Definition of bathymeteric zones according to van Hinte (1978). Vertical axis is Ma. Time scales of Berggren et al. (1985, 1995) are presented. PA = planktonic fossil assemblages, BA = benthonic fossil assemblages.

employed (Figs. 7a, b, 8, 9). As in well 2/4-C-11, the boundaries between the assemblages are based on the LADs of selected taxa. S = Sleipner Field.

Benthonic assemblages

ELPHIDIUM EXCAVATUM – HAYNESINA ORBICULARE ASSEMBLAGE

Designation: CS-AB.

Definition: The top of the assemblage extends to the uppermost investigated sample (200 m). The base is taken at the highest consistent occurrence of *Cassidulina teretis*.

Depth range: 200–380 m.

Material: Nine ditch cutting samples.

Age: Early to Middle Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).

Description: The assemblage contains a medium-rich benthonic fauna of calcareous foraminifera. *E. excavatum* occurs most frequently. Other important taxa include *H. orbiculare*, *C. reniforme*, *E. ustulatum* and *E. asklundi* (Fig. 7a).

Remarks: The benthonic foraminifera in this assemblage belong to characteristic Pliocene–Pleistocene taxa. All the recorded taxa are extant. Knudsen & Asbjörndóttir (1991) have described an *E. excavatum – H. orbiculare* assemblage Zone (Jo 6) from the well 30/13-2x in the British sector. This zone is slightly older than the Brunhes/Matuyama boundary.

ELPHIDIUM EXCAVATUM – CASSIDULINA TERETIS ASSEMBLAGE

Designation: CS-BB.

Description: The top of the assemblage is taken at the highest consistent occurrence of *Cassidulina teretis*. The base is marked by the highest occurrence of *Cibicides grossus*.

Depth range: 380–600 m.

Material: 11 ditch cutting samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Zone Jo 6 of Knudsen & Asbjörndóttir (1991) and Zone NSB 17 of King (1983).

Description: This interval contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum* occurs frequently throughout. Other important taxa include *C. teretis*, *H. orbiculare*, *C. reniforme*, *A. fluens*, *E. ustulatum* and *Q. seminulum* (Fig. 7a).

Remarks: The foraminifera in this interval are characteristic Pliocene–Pleistocene taxa, and all the recorded species are extant. Knudsen & Asbjörndottir (1991) describe a *C. teretis – E. excavatum* assemblage Zone (Jo 7) in Lower Pleistocene sediments of borehole 30/13-2X (British sector).

CIBICIDES GROSSUS ASSEMBLAGE

Designation: CS-CB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. grossus*. The base is marked by the highest occurrence of *M. pseudotepida*.

Depth range: 600–900 m.

Material: 18 ditch cutting samples.

Age: Late Pliocene to Early Pleistocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Subzones NSB 15a and b of King (1989), Zone Jo 8 of Knudsen & Asbjörndóttir (1991) and Zone NSR 12 of Gradstein & Bäckström (1996).

Description: This assemblage contains a very rich benthonic fauna of mainly calcareous foraminifera. Taxa are slightly more numerous in this assemblage than in the immediately overlying section. *E. excavatum*, *A. fluens* and *C. teretis* all occur frequently throughout. Other important species include *C. grossus*, *H. orbiculare*, *Islandiella islandica*, *Virgulina loeblichi* and *N. affine* (Fig. 7a).

Remarks: The LAD of *C. grossus*, in the southern part of the North Sea, is close to the Upper Pliocene/Pleistocene boundary. Further north it became extinct somewhat later (King 1989). This becomes apparent when one compares the LAD of *C. grossus* in wells 2/4-C-11 and 15/12–3. In the Ekofisk area, the LAD of *C. grossus* is just above the *N. pachyderma* (dextral) assemblage (Fig. 5a). In the Sleipner area, the LAD of *C. grossus* is quite high above this planktonic foraminiferal assemblage (Fig. 7a). On the Vøring Plateau, the base of the *N. pachyderma* (dextral) Zone is dated to 1.84 m.y. based on paleomagnetic investigations (Spiegler & Jansen 1989). This indicates that *C. grossus* becomes extinct as late as Early Pleistocene in the Sleipner area.

In this well we have placed the Upper Pliocene/Pleistocene boundary at the regional seismic reflector at ca. 670 m. However, it is not possible to conclude definitely that this level accurately represents the boundary.

MONSPELIENSINA PSEUDOTEPIDA ASSEMBLAGE

Designation: CS-DB.

Description: The top of the assemblage is taken at the highest occurrence of *M. pseudotepida*. The base is marked by the highest consistent occurrence of *C. limbatosuturalis* and *U. venusta saxonica*.

Depth range: 900–970 m.

Material: Four ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group and Utsira Formation.

Correlation: Subzone NSB 14b of King (1989), Zone NSR 12A of Gradstein & Bäckström (1996) and Zone Jo 10 of Knudsen & Asbjörndóttir (1991).

Description: This assemblage contains a very rich benthonic fauna of mainly calcareous foraminifera. *C. teretis* and *N. affine* are common. Other characteristic species include *M. pseudotepida*, *E. groenlandicum*, *A. fluens*, *B. marginata* and *C. lobatulus* (Fig. 7a).

Remarks: A *M. pseudotepida* Subzone (NSB 14b) is described from the lower part of the Upper Pliocene of the North Sea (King 1989).

CIBICIDOIDES LIMBATOSUTURALIS – UVIGERINA VENUSTA SAXONICA ASSEMBLAGE

Designation: CS-EB.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *C. limbatosuturalis* and *U. venusta saxonica*. The base is marked by the highest occurrence of *U. pygmea langenfeldensis*.

Depth range: 970–1110 m.

Material: Nine ditch cutting samples.

Age: Late Miocene to Early Pliocene.

Lithostratigraphic unit: Utsira Formation.

Correlation: Subzone NSB 14a and Subzone NSB 13b of King (1989).

Description: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. *C. limbatosuturalis*, *U. venusta saxonica*, *N. affine*, *A. fluens*, *C. teretis* (upper part) and *C. pliocarinata* (lower part) all occur frequently. Other important taxa include *P. bulloides*, *G. subglobosa*, *M. pseudotepida* and *F. boueanus* (Figs. 7a, b).

Remarks: King (1989) describe a *C. limbatosuturalis* Subzone (NSB 14a) and an *U. venusta saxonica* Subzone (NSB 13b) from Lower Pliocene to Upper Miocene deposits in the North Sea. According to King (1989), Subzone NSB 14a is very thin in the northern part of the North Sea. This is probably also the case in the Sleipner area, where the LADs of *C. limbatosuturalis* and *U. venusta saxonica* are found in the same sample. The result is that only Subzone NSB 13b can be recorded in well 15/12–3. The top of this zone is of Early Pliocene age, according to King (1989).

UVIGERINA PYGMEA LANGENFELDENSIS ASSEMBLAGE

Designation: CS-FB.

Definition: The top of the assemblage is taken at the highest occurrence of *U. pygmea langenfeldensis*. The base is marked by the highest occurrence of *Uvigerina* sp. A (King 1989).

Depth range: 1110–1160 m.

Material: Four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Utsira Formation and Hordaland Group.

Equivalent zones: Subzone NSB 13a of King (1989).

Description: This assemblage contains a moderately rich benthonic fauna of mainly calcareous foraminifera. There are somewhat fewer specimens than in the immediately overlying section. *U. pygmea langenfeldensis* and *C. pliocarinata* are both common. Other characteristic taxa include *P. bulloides*, *G. subglobosa*, *C. limbatosuturalis*, *B. elongata* and *Sphaeroidina bulloides* (Fig. 7b).

Remarks: U. pygmea langenfeldensis is described from Middle Miocene deposits of the North Sea (King 1989). *S. bulloides* is known from Upper Oligocene to Upper Miocene sediments of The Netherlands (Doppert 1980).

UVIGERINA SP. A ASSEMBLAGE

Designation: CS-GB.

Definition: The top of the assemblage is taken at the highest occurrence of *Uvigerina* sp. A (King 1989). The base is marked by the highest consistent occurrence of *Asterigerina guerichi staeschei*.

Depth range: 1160–1250 m.

Material: Five ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSB 12b of King (1989).

Description: This interval contains a moderately rich benthonic fauna of mainly calcareous foraminifera. There are somewhat fewer taxa in this interval than in the immediately overlying section. *U. pygmea langenfeldensis* occurs most frequently. Other characteristic taxa include *P. bulloides*, *G. subglobosa*, *C. limbatosuturalis*, *Uvigerina* sp. A, *B. elongata* and *S. bulloides* (Fig. 7b).

Remarks: A *Uvigerina* sp. A Subzone (NSB 12b) is described from Middle Miocene sediments in the North Sea (King 1989).

ASTERIGERINA GUERICHI STAESCHEI ASSEMBLAGE

Designation: CS-HB.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *A. guerichi staeschei*. The base is marked by the highest occurrence of *U. tenuipustulata*.

Depth range: 1250–1300 m.

Material: Five ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSB 11 of King (1989), probably Zone FD of Doppert (1980) and probably Zone NSR 9A of Gradstein & Bäckström (1996).

Description: This assemblage contains a moderately rich benthonic fauna of mainly calcareous foraminifera. There are slightly fewer specimens in this assemblage than in the immediately overlying section. No species occur frequently, but important taxa are *U. pygmea langenfeldensis*, *B. elongata*, *A. guerichi staeschei*, *U. semiornata saprophila*, *Cibicidoides d. peelensis*, *Hoeglundina elegans*, *N. affine* and *P. bulloides* (Fig. 7b).

Remarks: An *A. guerichi staeschei* Zone (NSB 11) is described from lower Middle Miocene deposits in the North Sea (King 1989).

UVIGERINA TENUIPUSTULATA ASSEMBLAGE

Designation: CS-IB.

Description: The top of the assemblage is taken at the highest occurrence of *U. tenuipustulata*. The base is marked by the highest occurrence of *Plectofrondicularia seminuda*.

Depth range: 1300–1340 m.

Material: Four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSB 10 of King (1989).

Description: Benthonic taxa are slightly more numerous in this assemblage than in the immediately overlying section. Calcareous foraminifera are dominant, but a few agglutinated forms are also recorded. *U. tenuipustulata* and *A. guerichi staeschei* occur most frequently. Other characteristic taxa include *B. elongata*, *Cibicidoides d. peelensis*, *H. elegans*, *S. compressa* (agglutinated), *Chilostomellina fimbriata*, *Stainforthia screibersina*, *P. bulloides*, *N. affine* and *Cibicidoides pachyderma* (Fig. 7b).

Remarks: An *U. tenuipustulata* Zone (NSB 10) is described from Lower Miocene sediments in the North Sea (King 1989).

PLECTOFRONDICULARIA SEMINUDA ASSEMBLAGE

Designation: CS-JB.

Definition: The top of the assemblage is taken at the highest occurrence of *P. seminuda*. The base is marked by the highest occurrence of *Bolivina antiqua*.

Depth range: 1340–1380 m.

Material: Three ditch cutting samples.

Lithostratigraphic unit: Hordaland Group.

Age: Early Miocene.

Correlation: Zone NSB 9 of King (1989).

Description: There are somewhat fewer taxa in this assemblage than in the immediately overlying assemblage. Calcareous benthonic foraminifera are dominant, but a few agglutinated species are also recorded. No species occur frequently, but important taxa are *Eponides umbonatus*, *A. guerichi staeschei*, *Turrilina alsatica*, *H. elegans*, *U. tenuipustulata*, *G. soldanii girardana*, *P. seminuda*, *A. guerichi guerichi*, *P. bulloides*, *N. affine*, *C. pachyderma* and *Haplophragmoides* sp. (agglutinated) (Fig. 7b).

Remarks: A *P. seminuda* Zone (NSB 9) is described from Lower Miocene deposits of the North Sea (King 1989).

BOLIVINA ANTIQUA ASSEMBLAGE

Designation: CS-KB.

Definition: The top of the assemblage is taken at the highest occurrence of *B. antiqua*. The base is marked by the highest occurrence of *Cibicides sulzensis*.

Depth range: 1380–1420 m.

Material: Two ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSB 8c of King (1989).

Description: This assemblage contains a moderately rich benthonic fauna of calcareous foraminifera. No species occur frequently, but important taxa are *B. elongata*, *A. guerichi staeschei*, *T. alsatica*, *H. elegans*, *U. tenuipustulata*, *C. fimbriata*, *B. antiqua*, *N. affine* and *P. bulloides* (Fig. 7b).

Remarks: King (1989) describes a *B. antiqua* Subzone (NSB 8c) from Upper Oligocene to lowermost Lower Miocene deposits in the North Sea. Here, the assemblage is of Early Miocene age.

CIBICIDES SULZENSIS ASSEMBLAGE

Designation: CS-LB.

Definition: The top of the assemblage is taken at the highest occurrence of *C. sulzensis*. The base of the assemblage is undefined.

Depth range: 1420–1520 m (lowermost studied sample).

Material: Eight ditch cutting samples.

Age: Late Oligocene to Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Probably Subzone NSB 8c or Subzone NSB 8b of King (1989), and probably the lower part of Zone NSR 8B or Zone NSR 8A of Gradstein & Bäckström (1996).

Description: Taxa are slightly more numerous in this interval than in the immediately overlying section. Calcareous forms are most important, but agglutinated forms are also common. No species are very numerous, but important calcareous taxa are *C. sulzensis*, *E. umbonatus*, *B. elongata*, *A. guerichi staeschei*, *T. alsatica*, *H. elegans*, *U. tenuipustulata*, *B. antiqua*, *Trifarina gracilis*, *Valvulineria petrolei*, *Karreria fallax*, *Buliminella carteri*, *Nonion pompilioides*, *P. bulloides* and *N. affine*. Important agglutinated taxa are *S. compressa*, *Bathysiphon eocenicus*, *Ammodiscus* sp. A, *A. biedai*, *Glomospira charoides*, *R. rotundidorsatum* and *Spirosigmoilinella* spp. (Fig. 7b).

Remarks: *C. sulzensis* is originally described from Upper Oligocene deposits in Belgium (Batjes 1958). According to King (1989), the following taxa are known from Lower Oligocene to Lower Miocene deposits in the North Sea: *T. alsatica*, *V. petrolei*, *K. fallax*, *S. compressa*, *Ammodiscus* sp. A and *A. biedai*. According to Batjes (1958), *N. pompilioides*, *T. gracilis* and *B. carteri* are known from Upper Oligocene sediments in Belgium.

Planktonic assemblages

UNDEFINED INTERVAL

Depth range: 200 (uppermost investigated sample)–790 m.

Material: 30 ditch cutting samples.

Lithostratigraphic unit: Nordland Group.

In-place assemblage composition: Just a few specimens of *N. pachyderma* (sinistral, unencrusted) are recorded from the upper and lower parts of this interval.

Reworked assemblage composition: *Heterohelix* sp. and *Hedbergella* sp. are recorded sporadically throughout the interval. These taxa are derived from Upper Cretaceous sediments.

NEOGLOBOQUADRINA PACHYDERMA (DEXTRAL) ASSEMBLAGE

Designation: CS-AP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. pachyderma* (dextral). The base is marked by the highest occurrence of *N. atlantica* (dextral).

Depth range: 790–840 m.

Material: Three ditch cutting samples.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *N. pachyderma* (dextral) Zone of Weaver (1987), Weaver & Clement (1987) and Spiegler & Jansen (1989); Subzone NSP 16a of King (1989).

Description: Although planktonic foraminifera are sparse in this interval, they are significantly more common than in the immediately overlying section. Most important species are *N. pachyderma* (dextral) and *N. pachyderma* (sinistral, unencrusted). *T. quinqueloba* and the Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. are also recorded (Fig. 7a).

Remarks: A *N. pachyderma* (dextral) Zone is described by Weaver (1987) and Weaver & Clement (1987) from the North Atlantic (DSDP Leg 94) and by Spiegler & Jansen (1989) from the Vøring Plateau in Upper Pliocene deposits. On the Vøring Plateau, the zone is accurately dated to 1.84–1.7 Ma.

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) ASSEMBLAGE

Designation: CS-BP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (dextral). The base is marked by the highest occurrence of *G. bulloides*.

Depth range: 840–850 m.

Material: One ditch cutting sample.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: Upper *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989).

Description: Planktonic foraminifera are slightly more numerous in this assemblage than in the immediately overlying assemblage. The following taxa are recorded: *N. atlantica* (dextral), *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral) and *T. quinqueloba* (Fig. 7a).

Remarks: An upper *N. atlantica* (dextral) Zone is described from the Vøring Plateau in Upper Pliocene deposits, and is accurately dated to 2.3–1.84 Ma (Spiegler & Jansen 1989).

GLOBIGERINA BULLOIDES ASSEMBLAGE

Designation: CS-CP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. bulloides*. The base is marked by the highest occurrence of *N. atlantica* (sinistral).

Depth range: 850–860 m.

Material: One ditch cutting sample.

Age: Late Pliocene.

Lithostratigraphic unit: Nordland Group.

Correlation: *G. bulloides* Zone of Weaver & Clement (1986).

Description: In this assemblage, planktonic foraminifera are as numerous as in the immediately overlying assemblage. *G. bulloides*, *N. atlantica* (dextral), *N. pachyderma* (dextral) and *N. pachyderma* (sinistral, unencrusted) occur most frequently. Other species include *T. quinqueloba* and the redeposited Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. (Fig. 7a).

Remarks: A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Upper Pliocene deposits and is accurately dated to 2.3–2.1 Ma (Weaver & Clement 1986).

GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: CS-DP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. atlantica* (sinistral). The base is marked by the highest occurrence of *N. acostaensis*.

Depth range: 860–1010 m.

Material: 10 ditch cutting samples.

Age: Early to Late Pliocene.

Lithostratigraphic unit: Nordland Group and Utsira Formation.

Correlation: *N. atlantica* (sinistral) Zone of Weaver & Clement (1986), *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989) and Subzone NSP 15d of King (1989).

Description: This interval contains a moderately rich planktonic foraminiferal fauna. Taxa are significantly more numerous in this interval than in the immediately overlying section. *G. bulloides*, *N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral) occur most frequently. Other species include *Globigerina falconensis*, *T. quinqueloba* and the Upper Cretaceous forms *Hedbergella* sp. and *Heterohelix* sp. (Fig. 7a).

Remarks: A *N. atlantica* (sinistral) Zone is described from the North Atlantic in Upper Pliocene deposits (Weaver & Clement 1986), and from the Vøring Plateau in Lower to Upper Pliocene deposits (Spiegler & Jansen 1989). The LAD of *N. atlantica* (sinistral) is, in both areas, ca. 2.3 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). On the Vøring Plateau, there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this. *G. bulloides* is also found in the warmest interglacials of the last 1 Ma (Kellogg 1977).

NEOGLOBOQUADRINA ATLANTICA (DEXTRAL) – *NEOGLOBOQUADRINA ACOSTAENSIS* ASSEMBLAGE

Designation: CS-EP.

Definition: The top of the assemblage is taken at the highest occurrence of *N. acostaensis*. The base is marked by the highest occurrence of *B. fragori* and *B. subfragori*.

Depth range: 1010–1110 m.

Material: Six ditch cutting samples.

Age: Late Miocene.

Lithostratigraphic unit: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989); *N. atlantica* (dextral)/*N. acostaensis* Zone of Weaver (1987) and Weaver & Clement (1987); Subzone NSP 15a of King (1989).

In-place assemblage composition: There are somewhat fewer planktonic foraminifera in this interval than in the immediately overlying section. *N. acostaensis*, *G. bulloides* and *N. atlantica* (sinistral) occur most frequently. Other important taxa include *N. atlantica* (dextral), *T. quinqueloba*, *N. pachyderma* (dextral), *Globigerinita inflata* (upper part) and *G. puncticulata* (lower part) (Figs. 7a, b).

Reworked assemblage composition: A few specimens of *B. clodiusi* are recorded from the middle part of the interval. This form has probably been derived from deposits which correspond to the immediately underlying assemblage.

Remarks: Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau, and Weaver (1987) and Weaver & Clement (1987) record a *N. atlantica* (dextral)/*N. acostaensis* Zone from Upper Miocene sediments in the North Atlantic (DSDP Leg 94). *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989; Müller & Spiegler 1993). King (1989) describes a *N. acostaensis* Zone from Upper Miocene deposits in the North Sea.

BOLBOFORMA FRAGORI – BOLBOFORMA SUBFRAGORI ASSEMBLAGE

Designation: CS-FP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. fragori* and *B. subfragori*. The base is marked by the highest occurrence of *Bolboforma badenensis*.

Depth range: 1110–1200 m.

Material: Six ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Utsira Formation and Hordaland Group.

Correlation: B. fragori/B. subfragori Zone of Spiegler & Müller (1992) and Müller & Spiegler (1993) and Subzone NSP 14a of King (1983).

Description: This assemblage contains a rich planktonic fauna of foraminifera and *Bolboforma*. *Bolboforma* are dominant, while foraminifera are subordinate. *B. clodiusi* is the most common *Bolboforma*. Other important species include *B. fragori*, *B. subfragori*, *B. pseudohystrix* and *B. laevis*. *B. metzmacheri*, *B. aculeata* and *B. compressispinosa* are also recorded. *G. bulloides*, *N. atlantica* (sinistral), *N. atlantica* (dextral) and *N. acostaensis* are the most important foraminifera (Fig. 7b).

Remarks: The known stratigraphic ranges of the most important planktonic foraminifera are discussed above under the descriptions of the CE-DP and CS-EP assemblages. A *B. fragori/B. subfragori* Zone is described from deposits with an age of ca. 11.5–9.6 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

Spiegler & Müller (1992) and Müller & Spiegler (1993) describe a *B. metzmacheri* Zone (lowermost Upper Miocene) above the *B. fragori/B. subfragori* Zone in the North Atlantic and on the Vøring Plateau. In well 15/12–3, *B. metzmacheri* does not reach higher than *B. fragori* and *B. subfragori*. This may indicate that *B. metzmacheri* is caved from the overlying assemblage, without being recorded there, or that the LAD of this form is slightly different in the Sleipner area than in the North Atlantic and in the Norwegian Sea.

BOLBOFORMA BADENENSIS – BOLBOFORMA RETICULATA ASSEMBLAGE

Designation: CS-GP.

Definition: The top of the assemblage is taken at the highest occurrence of *B. badenensis*. The base is marked by the highest consistent occurrence of *Globigerina praebulloides*.

Depth range: 1200–1260 m.

Material: Four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: B. badenensis and *B. reticulata* Zones of Spiegler & Müller (1992); *B. badenensis/B. reticulata* Zone of Müller & Spiegler (1993), and probably Zone NSP 13 of King (1983).

Description: This assemblage contains a rich planktonic fauna of mainly *Bolboforma*. A few planktonic foraminifera are also recorded. *B. clodiusi*, *B. pseudohystrix*, *B. badenensis* and *B. reticulata* are the most common *Bolboforma*. Other species include *B. laevis*, *B. subfragori*, *B. fragori*, *B. compressispinosa* and *B. compressibadenensis*. The few foraminifera include *G. bulloides*, *N. atlantica* (sinistral) and *N. acostaensis* (Fig. 7b).

Remarks: Spiegler & Müller (1992) describe a *B. badenensis* Zone and a *B. reticulata* Zone from the North Atlantic, and Müller & Spiegler (1993) describe a *B. badenensis/B. reticulata* Zone from the Vøring Plateau. These zones are recorded from deposits with an age of ca. 14–11.5 Ma (Spiegler & Müller 1992).

GLOBIGERINA PRAEBULLOIDES ASSEMBLAGE

Designation: CS-HP.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *G. praebulloides*. The base is marked by the highest occurrence of *G. ciperoensis* and the highest consistent occurrence of *G. woodi*.

Depth range: 1260–1300 m.

Material: Four ditch cutting samples.

Age: Middle Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 12 of King (1983) and Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This interval contains a rich planktonic fossil assemblage of radiolaria, *Bolboforma*, foraminifera and pyritized diatoms. Radiolaria and *Bolboforma* are dominant, while foraminifera and diatoms being subordinate. *B. pseudohystrix* is the most common *Bolboforma*, followed by *B. reticulata*, *B. badenensis*, *B. compressibadenensis* and *B. subfragori*. *G. praebulloides* is the most common foraminifer. Other species include *N. mayeri*, *G. angustiumbilicata*, *G. woodi* and *S. disjuncta* (Fig. 7b).

Remarks: G. praebulloides is known from Oligocene to lower Upper Miocene (common in Middle Miocene) deposits in the North Atlantic (Poore 1979) and from Oligocene to lower Middle Miocene deposits in the North Sea (Gradstein & Bäckström 1996). *G. woodi* is known from Upper Oligocene to Lower Pliocene sediments in the North Atlantic (Poore 1979). *S. disjuncta* is known from Lower to Middle Miocene sediments in the North Sea (Gradstein & Bäckström 1996). *G. angustiumbilicata* is known from Upper Oligocene to Lower Pliocene deposits (Kennet & Srinivasan 1983). This indicates an early Middle Miocene age for this interval. The *Bolboforma* recorded in this interval are probably caved.

GLOBIGERINA CIPEROENSIS – GLOBIGERINA WOODI ASSEMBLAGE

Designation: CS-IP.

Definition: The top of the assemblage is taken at the highest occurrence of *G. ciperoensis* and the highest consistent occurrence of *G. woodi*. The base is marked by the highest occurrence of Diatom sp. 4 (King 1983).

Depth range: 1300–1340 m.

Material: Four ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Lower part of Zone NSR 8B of Gradstein & Bäckström (1996).

Description: This interval contains a rich planktonic fossil assemblage of foraminifera, radiolaria and pyritized diatoms. *G. ciperoensis* and *G. woodi* occur most frequently of the foraminifera. Other important species are *G. praebulloides*, *G. angustiumbilicata*, *G. zealandica*, *G. praescitula* and *G. quadrilobatus triloba* (Fig. 7b).

Remarks: The known stratigraphic ranges of most of the planktonic foraminifera are discussed above under the description of assemblage CS-GP. *G. ciperoencis* is described from Upper Oligocene to Lower Miocene deposits in the North Atlantic (Leg 49) (Poore 1979) and in the North Sea (Gradstein & Bäckström 1996). *G. zealandica* and *G. praescitula* are known from Lower Miocene to lower Middle Miocene sediments from the North Atlantic (Poore 1979). This indicates an Early Miocene age for this interval.

DIATOM SP. 4 ASSEMBLAGE

Designation: CS-JP.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 4 (King 1983). The base is marked by the highest occurrence of Diatom sp. 3 (King 1983).

Depth range: 1340–1460 m.

Material: Nine ditch cutting samples.

Age: Early Miocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Definition: This assemblage contains a rich planktonic fossil assemblage of pyritized diatoms, foraminifera and radiolaria. Diatom sp. 4 occurs throughout the zone. *G. ciperoensis* and *G. woodi* occur most frequently of the foraminifera. Other important species include *G. praebulloides*, *G. zealandica*, *G. praescitula*, *G. angustiumbilicata* and *S. disjuncta* (Fig. 7b).

Remarks: The known stratigraphic ranges of the planktonic foraminifera are discussed previously, under the descriptions of the CS-HP and CS-IP assemblages. Diatom sp. 4 is known from Lower Miocene deposits in the North Sea (King 1983).

DIATOM SP. 3 ASSEMBLAGE

Designation: CS-KP.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 3 (King 1983). The base of the assemblage is undefined.

Depth range: 1460–1520 m.

Material: Four ditch cutting samples.

Age: Late Oligocene.

Lithostratigraphic unit: Hordaland Group.

Correlation: Subzone NSP 9c of King (1989).

Description: This interval contains a moderately rich planktonic fossil assemblage of pyritized diatoms and foraminifera. Diatom sp. 3 and Diatom sp. 4 occur throughout. *G. praebulloides*, *G. angustiumbilicata*, *S. disjuncta* and *G. ciperoensis* occur most frequently among foraminifera (Fig. 7b).

Remarks: Diatom sp. 3 is known from Upper Oligocene to lowermost Lower Miocene deposits in the North Sea (King 1989). The stratigraphic range of the benthonic foraminifera in this interval indicates that Lower Miocene can be ruled out. Most of the recorded planktonic foraminifera are probably caved.

Lithology and lithostratigraphy

Upper Oligocene to lower part of Middle Miocene (Hordaland Group)

The petrophysical logs and ditch cutting samples show that this section contains mostly clay, with small proportions of sand, silt and limestone.

Upper part of Middle Miocene to lower part of Upper Pliocene (Utsira Formation)

Light grey sand dominates this interval. The sand contains mainly quartz grains, but some glauconite grains are also present. The lower part of the section also contains quite a large proportion of silt and clay. Mollusc fragments are common in the sandiest part of the section.

Robertson Research (1996) describes a Tampen Spur Sandstone Member (informal name) which lies above and is separated from the Utsira Formation by a clay-rich interval. According to Robertson Research (1996), the Tampen Spur Sandstone Member is of latest Early Pliocene age and is mainly located in the northern North Sea, but can perhaps also be followed to the Norwegian Quadrant 15.

The sandy section in well 15/12–3 is interpreted as a single unit not subdivided by significant clay intervals. This sandy unit corresponds to the Utsira Formation of the type well (Isaksen & Tonstad 1989), and in this paper is called the Utsira Formation. However, the age of its upper part is younger than in the type well. The relation between the younger part of the sandy unit in well 15/12–3 and the Tampen Spur Sandstone Member of Robertson Research (1996) has not been investigated in this study.

Upper part of Upper Pliocene and Pleistocene (Nordland Group)

The samples in the lower part of the Pleistocene/upper part of the Upper Pliocene section contain a diamicton dominated by clay, but with a large proportion of pebbles of both crystalline and sedimentary origin. These sediments are attributed to glaciomarine environments.

The ditch cutting samples from the uppermost ca. 300 m of the well contain a sandy diamicton. The petrophysical logs from this section show that the sand is concentrated in thick beds with fine-grained intervals between. These sediments are interpreted as glacial and glaciofluvial depositions.

The large proportion of ice-rafted pebbles indicates that sediments are deposited after the great increase in ice-rafted detritus at the Vøring Plateau. This event started at about 2.6 Ma (Jansen & Sjøholm 1991; Fronval & Jansen 1996).

Paleoenvironments

Upper Oligocene

Pyritized diatoms dominate the planktonic fossil assemblage in this interval. Foraminifera and radiolaria are far less numerous. Calcareous foraminifera dominate the benthonic fauna, but agglutinated forms are also common. Calcareous benthonic deep water indicators such as *P. seminuda* and *C. sulzensis* (Skarbø & Verdenius 1986) are recorded. The content of agglutinated foraminifera is probably a response to somewhat restricted vertical water circulation. The Upper Oligocene section was probably deposited in an upper bathyal environment.

Lower Miocene

The Lower Miocene contains a rich planktonic assemblage including foraminifera, radiolaria and pyritized diatoms. The deep water indicators *N. affine* and *P. bulloides* occur consistently throughout. Several more deep water indicators, such as *P. seminuda*, *B. antiqua* and *C. sulzensis* (Skarbø & Verdenius 1986), are also recorded. This section was probably deposited in an upper bathyal environment.

Middle Miocene

In this interval planktonic fossils are common. Species of *Bolboforma* is the dominant group. Planktonic foraminifera are far less numerous, except in the lower part, where these are also common. The deep water indicators *N. affine* and *P. bulloides* occur consistently throughout the interval. This section was probably deposited in an outer neritic environment.

Upper Miocene and Lower Pliocene

The Upper Miocene and Lower Pliocene make up of the bulk of the sandy Utsira Formation. According to Isaksen & Tonstad (1989), the Utsira Formation is a shallow marine deposit. However, the consistent occurrence of planktonic foraminifera and *Bolboforma*, and the benthonic deep water indicators *N. affine* and *P. bulloides*, suggest that the formation was deposited in deeper water in this area. According to Rundberg (1989), the northern North Sea area was a shallow marine passage between deeper water to the south and north during the Late Miocene. The corresponding sediments in the Ekofisk area are deep water depositions. The depositional environment in the Sleipner area was probably in a middle position between the Ekofisk area and the northern North Sea area, and was probably middle to outer neritic.

Upper Pliocene

Planktonic foraminifera are common throughout most of this section; the largest proportion is found in its middle part. The upper and lower parts contain fewer planktonic specimens. The deep water indicator *N. affine* and the shallow water indicators of the genus *Elphidium* occur consistently in the Upper Pliocene. The Upper Pliocene section was probably deposited in a middle neritic environment. Glacigenic material and the consistent occurrence of both boreal and arctic benthonic foraminifera indicate cold to transitional water conditions.

Pleistocene

The Pleistocene section contains very few planktonic foraminifera, indicating little contact with open ocean and fairly shallow marine conditions. Shallow marine conditions are also indicated by a large proportion of the benthonic genus *Elphidium*. A large proportion of ice-rafted pebbles in the sediments and a high content of arctic benthonic foraminifera indicate cold water conditions. The Pleistocene section was probably deposited in an inner neritic environment.

Summary and correlation between well sites

Upper Oligocene to lower part of Lower Miocene

The unit below the intra-Lower Miocene reflector (ILM on Fig. 4), i.e. the lower part of the Lower Miocene and the investigated part of the Upper Oligocene, contains mostly clay with small proportions of silt, sand and some limestone stringers.

No planktonic index fossils are found in the upper part of this unit in the Ekofisk well. In the lower part, the same diatom index fossils are found in both areas (assemblages CE-KP/CE-LP and CS-JP/CS-KP). The benthonic fauna is very different in the two areas. In the Ekofisk well almost exclusively agglutinated forms have been recorded, while in the Sleipner well there are almost exclusively calcareous forms in the upper part of the unit. In the lower part calcareous forms are dominant, but some agglutinated forms are also found. This indicates deposition in a somewhat restricted basin in the Ekofisk area, as opposed to the better ventilated basin at the Sleipner site. The water depth was probably upper bathyal in both areas (Fig. 9).

Upper part of Lower Miocene to lower part of the Middle Miocene

The ILM reflector (Fig. 4), which lies in the upper part of the Lower Miocene in both wells, marks the base of two basins with a threshold in between. The wells penetrate the deepest part of each basin. The IMM reflector (Fig. 4) is developed in the upper part of the Middle Miocene in both wells. Below this reflector there is a hiatus in the Ekofisk well, and the middle part of Middle Miocene is missing in this area. In the Sleipner well it is not possible to detect a hiatus. In both areas this unit contains mostly clay with small proportions of silt and sand.

The same planktonic index fossils are found in both areas. However, in the lowermost planktonic assemblages (CE-JP and CS-IP), there are far more *G. woodi* compared to *G. ciperoensis* in the Sleipner area than in the Ekofisk area. This indicates somewhat different pathways to the open ocean from the two areas. In addition, the benthonic index foraminifera are identical in the two areas within the lower part of the unit (assemblages CE-JB and CS-IB). This is not the case for the upper part, but this interval can be correlated by means of the planktonic fossils. Throughout the whole unit there are far more agglutinated foraminifera in the Ekofisk area than in the Sleipner area. This indicates deposition in a more restricted basin in the Ekofisk area. The water depth was probably upper bathyal in both areas during the late Early Miocene, and during the early Middle Miocene in the Ekofisk area. In the Sleipner area the water depth was probably outer neritic during the early Middle Miocene (Fig. 9). The late Cenozoic climatic cooling had not yet commenced (Fronval & Jansen 1996).

The sedimentary unit between the seismic reflectors ILM and IMM can only be detected on seismic data in the Central Graben. This unit thins out on the flanks of the basin. These sediments have probably very little permeability, since they function as a pressure barrier in the Tertiary in the Central Graben.

Upper part of Middle Miocene to Lower Pliocene

Lower Pliocene, Upper Miocene and the uppermost part of Middle Miocene form one seismic unit. This unit thins towards north, and the IMM reflector lies much deeper in the Ekofisk area than in the Sleipner area (Fig. 4). In the Ekofisk area the unit contains mostly clay. Northwards there is a shift in lithology, and the deposits turn into the Utsira sand in the Sleipner area.

The same planktonic index fossils are found in both areas. This is also the case for the benthonic fauna in the Lower Pliocene and upper part of the Upper Miocene, but in the lower part of the Upper Miocene and upper part of the Middle Miocene, the benthonic fauna is somewhat different. In the Ekofisk well this section contains a large proportion of agglutinated forms, while the Sleipner well contains only calcareous foraminifera. This indicates deposition in a deeper and more restricted basin in the Ekofisk area than at the Sleipner site. A greater water depth in the Ekofisk area is also indicated by the faunas in the Early Pliocene and late part of the Late Miocene, but at that time there was well developed vertical water circulation in both areas (Fig. 9). The foraminiferal fauna indicates an upwards cooling trend.

Upper Pliocene

The BUTp reflector (Fig. 4) lies at approximately the same depth level in the two areas, and the Upper Pliocene section thins towards the north. In the Sleipner area the BUTp reflector marks the top of the Utsira Formation, and in well 15/12–3 the top of this formation is slightly above the Lower/Upper Pliocene boundary.

In the Ekofisk area the Upper Pliocene section contains a clay-rich diamicton with small proportions of sand, silt and ice-rafted pebbles (down to 900 m). In the Sleipner area the Upper Pliocene section above the Utsira Formation also contains a clay-rich diamicton, but with larger proportions of silt, sand and ice-rafted pebbles. The Utsira Formation is dominated by sand.

The same benthonic and planktonic index foraminifera are found in both areas. The only major exception is the upper *N. atlantica* (dextral) assemblage, which is only recorded in well 2/4-C-11. However, this unit is very thin both in the Ekofisk area and on the Vøring Plateau (Spiegler & Jansen 1989), and therefore its absence does not necessarily suggest the presence of a hiatus. The water was probably somewhat deeper in the Ekofisk (outer to middle neritic) than in the Sleipner area (middle neritic) in the early part of the Late Pliocene. In the late part of Late Pliocene the water depth was probably middle neritic in both areas (Fig. 9). The water conditions during the Late Pliocene were probably cold to transitional.

The Upper Pliocene is relatively complete in both wells, and its lower part, i.e. deposits from 3.5–2.6 Ma, is also present. In most areas on the Norwegian continental shelf north of the Central Graben, there is probably a hiatus in the Upper Pliocene, and the lower part of Upper Pliocene is probably missing (Eidvin & Riis 1992; Eidvin et al. 1993a, 1998a, 1998b).

Pleistocene

The seismic profile (Fig. 4) shows that the Pleistocene deposits thicken towards north, from the Ekofisk towards the Sleipner area. The lower part of the Pleistocene section in well 2/4-C-11 contains a clay-rich diamicton with small proportions of sand, silt and ice-rafted pebbles. In well 15/12–3 this part also contains a diamicton dominated by clay, but with a much larger proportion of ice-rafted pebbles. The Lower Pleistocene deposits are, in both areas, interpreted as glaciomarine and marine sediments. The uppermost ca. 300 m of both wells 2/4-C-11 and 15/12-3 (Middle to Upper Pleistocene) contain thick sand beds with fine-grained intervals between. These deposits are interpreted as glacial and glaciofluvial sediments.

The same Pleistocene benthonic index foraminifera are found in both areas (Figs. 8, 9). However, the LAD of *C. grossus* is somewhat later in the Sleipner area than in the Ekofisk area. The planktonic foraminifera are too few to erect a planktonic zonation scheme. The foraminiferal fauna indicates shallow marine, cold water conditions in both areas (Fig. 9).

The Lower Pleistocene accumulation area in the Central Graben probably represents the depocenter for the sediments transported by the rivers flowing northwards from the northwestern European mainland. The Middle and Upper Pleistocene depositional processes were probably controlled mainly by the three latest and largest glaciations, i.e. Elsterian, Saalian and Weichselian (Cameron et al. 1987; Sejrup et al. 1987).

Acknowledgements. – The authors acknowledge Halliburton Geophysical Services for permission to publish seismic lines. They extend thanks to Bjørg Ruus, Sigrun Torrissen and Finn Moe for their careful and accurate technical assistance during this project, and to Rune Goa and Astrid Larsen for preparation of the illustrations. They are also grateful to Claus Beyer, Gøran Åberg, Helge Stray, Robert Williams and Kaare Ulleberg for their co-operation and to Jenö Nagy, Felix Gradstein, Eystein Jansen, Henrik Jordt, Gitte V. Laursen and Alex Cullum for their comments on the manuscript. Sven Bäckström, Karen Luise Knudsen and one anonymous reviewer reviewed the manuscript and offered numerous suggestions.

Manuscript received March 1998

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Paper 3:

Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands

Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands.

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Eidvin, T. & Rundberg, Y.: Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidsskrift*, Vol....., pp........, Oslo......., ISSN...........

This study is based on biostratigraphic analysis of upper Cainozoic strata in eight exploration and production wells from the Tampen area (Snorre and Visund fields), and one well from the Troll Field. Dating of the units is based primarily on planktonic and benthic foraminifera. Eleven fossil assemblages have been defined in sediments from the Lower Oligocene to the Pleistocene. In addition, strontium isotope, lithologic and petrophysical log analyses have been performed, and the studied wells have been correlated along regional 2-D and 3-D seismic lines.

In the Troll area the Pleistocene rests unconformably on the Lower Oligocene. The upper part of the Upper Oligocene is absent in all the Tampen wells. In the Visund area (block 34/8) there is a hiatus of more than 2 m.y. between Oligocene and Lower Miocene strata, and in the Snorre area (blocks 34/4 and 34/7) there is a hiatus of more than 18 m.y. between Oligocene and Upper Miocene deposits.

The Neogene section has been subdivided into five major lithologic units. In the Visund area, a Lower Miocene unit (1) of dominantly fine-grained, silty sediments has been identified. A major hiatus separates this unit from the overlying Utsira Formation (2), which in the northern North Sea comprises a thick lower part composed of quartzose sand and a thinner upper part of glauconitic sand. The main sands of the Utsira Formation are not present in any of the studied wells, but preliminary results from well 35/11-1 indicate a Late Miocene to possible latest Middle Miocene age for this unit. The glauconitic part of the Utsira Formation (Late Miocene to earliest Early Pliocene in age) overlies the Oligocene strata in the

Snorre area and the Lower Miocene deposits in the Visund area. To the east it may drape over the main Utsira Formation sands or partly interfinger with these. It is overlain by a basal upper Pliocene unit (3) consisting of gravity flow deposits. Cores from this unit exhibit ice-rafted pebbles and have a glacio-marine affinity. A thick complex of Upper Pliocene prograding wedges (4) downlap the basal Pliocene unit in the Tampen area and the Utsira Formation in the eastern part of the basin. It is unconformably overlain by a Pleistocene unit at the top (5).

An important feature of the Neogene succession is a large incised valley/canyon system which is developed in a north-westerly direction from block 35/8 (off Sognefjorden) to about 62°N. This erosive system cuts into the basal Upper Pliocene unit in block 34/3 and is thus much younger than has been previously suggested.

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Introduction

Sands are commonplace in the Lower Neogene succession of the northern North Sea. These sands usually occur at the base of the Neogene and are separated by a large hiatus from the Oligocene sediments of the underlying Hordaland Group (Isaksen & Tonstad 1989). They reach a gross thickness in excess of 200 m in the central parts of the basin (Quadrant 30; Fig. 1), and are distributed laterally as a composite sand body with an elongate, north-south orientation.

The Utsira Formation was first defined by Deegan & Scull (1977) and later by Isaksen & Tonstad (1989) as a sand rich interval of Middle to Late Miocene age (well type section in 16/1-1).

However, the term "Utsira Formation" has commonly been used imprecisely by geological consultants and other scientists/geologists, and has in many cases been applied to all sandy Neogene units in the northern North Sea, regardless of lithofacies, age and depositional environment. In the Snorre and Visund areas (Fig. 1), for example, Upper Pliocene turbiditic sands and lowstand sequences have been included in the Utsira Formation. The reason for this is that these sands were previously assigned a Miocene age, based on Miocene index fossils which we now consider to be reworked. However, our work on recently cored sections and sidewall cores from wells in the Snorre and Visund fields provides new information regarding the Neogene succession of this part of the North Sea.

Our investigation of nine hydrocarbon exploration and production wells is a combined biostratigraphical, seismostratigraphical, lithostratigraphical and geochemical study. The main purpose was to improve the chronology of the Neogene sequences and to better constrain the age of the main sequence boundaries. A secondary objective has been to use microfauna to interpret depositional environments. Emphasis has been placed on the lower part of the Nordland Group (Isaksen & Tonstad 1989), including the Utsira Formation. The prograding Upper Pliocene unit has been studied in details in two wells, whereas the Pleistocene is considered in one well only. All absolute ages referred to in the present study are based on Berggren et al. (1995). In order to ensure that the results reported here are consistent with electric logs and other technical information, all depths are expressed as metres below the rig floor (m RKB).

In the Viking Graben, the main period of hydrocarbon generation took place during the late Cainozoic. Precise dating of the Neogene succession is therefore important in oil and gas exploration because it provides constraints on burial history models. An improved chronology of the Neogene succession is also of crucial importance in understanding the basin evolution and sedimentary history of the area.

Previous work

The northern North Sea has been extensively explored, and many hydrocarbon exploration and production wells have been drilled. Unpublished routine biostratigraphic datings for most of these wells have been performed by consultants commissioned by the oil companies. However, the upper Cainozoic succession has usually not been given high priority, and the datings are often inadequate.

Based on the analysis of mainly ditch cutting samples from a number of wells, King (1983, 1989) published a detailed foraminiferal zonation for the Cainozoic of the entire North Sea. A detailed probabilistic foraminiferal zonation was established by Gradstein & Bäckström (1996) for the North Sea and the Haltenbanken areas.

In recent years, several papers and reports have been published dealing with the chronology of upper Cainozoic deposits in exploration wells from the northern North Sea area; Eidvin et al. (1991), Steurbaut et al. (1991), Seidenkrantz (1992; Upper Pliocene and Pleistocene), Eidvin & Riis (1992) and Gradstein et al. (1992, 1994). Rundberg & Smalley (1989) performed age determinations from exploration wells based on strontium isotope stratigraphy. In the present paper we present the results of new analyses of the three wells described in the report by Eidvin & Riis (1992) and one of the wells described in that of Eidvin et al. (1991) and the paper of Rundberg & Smalley (1989). In addition the present study includes analyses of five new wells.

Sejrup et al. (1995) have investigated cores from a geotechnical borehole from the Troll Field (Fig. 1), which penetrated the base Pleistocene unconformity. The cores from this borehole were subjected to palaeomagnetic, amino acid and foraminiferal analyses.

Rokoengen et al. (1983), Rundberg (1989), Jordt et al. (1995 and in press), King et al. (1996), Sejrup et al. (1996), Gregersen et al. (1997), Gregersen (1998) and Martinsen et al. (1999) have performed important regional seismic studies from the Neogene succession of the northern North Sea area.

The study area and geologic setting

Eight of the wells selected for this study are situated in the Tampen Spur area of the northern North Sea (Fig. 1). Wells 34/7-1, 34/4-7 and 34/4-6 are located on the Snorre field. Wells 34/8-9S, 34/8A-1H, 34/8-1, 34/8-3A are situated on the Visund field and 34/2-4 is located on the northern Tampen Spur close to the Møre Basin.

The Tampen Spur is a Mesozoic structural high situated west of the northern Viking Graben. The high exhibits a NNE-orientation, plunging towards the Møre Basin to the north. The structure at Lower Cretaceous level is overlain by Upper Cretaceous and Cainozoic sediments. Deep marine mudstones dominate the lower Tertiary sediments of the northernmost North Sea. Turbiditic sands are found adjacent to the Shetland Platform to the west, and to the Fennoscandian High to the east. The Eocene-Oligocene transition is characterised by an abrupt lithological shift from greenish, very fine-grained mudstones, to brownish, coarser mudstones. This change in lithology marks a shift to a colder climate, and also coincides with the onset of the "mid-Tertiary" compressional regime that affected the entire North Atlantic region. Oligocene sediments comprise coarsening-upward mudstones with glauconitic siltstones at the top, introducing shallower marine environments at the transition to the Neogene deposits (Rundberg 1989).

Seismic stratigraphic framework

A cross-section showing the post-Oligocene succession in the Norwegian part of the northern North Sea is illustrated on the seismic line in Fig. 2. The succession has been subdivided into sequences as follows: (1) the lower Miocene sequence at the base; (2) the Middle/Upper Miocene-basal Lower Pliocene sequence comprising the Utsira Formation; (3) the basal Upper Pliocene sequence; (4) the thick prograding Upper Pliocene complex; and (5) the Pleistocene sequence at the top.

Along the axis of the basin, there is a well-defined seismic sequence (1) reaching about 200 m in thickness (Fig. 2). The sequence (Early Miocene in age) has a low amplitude, continuous reflection pattern internally, and appears to onlap the basin margins. The base is marked by onlap onto the top Oligocene unconformity. The top is defined to the west by toplap truncation, and to the east by a prominent reflector marking the base of the sandy Utsira Formation. The sequence pinches out to the east and west respectively (Fig. 2). It is only recorded in wells in the Visund Field in the Tampen area. The areal distribution of the sequence is shown in Fig. 1. To the north, the sequence pinches out at about 61°30'N. Southwards, the sequence is more difficult to map due to the gradual development of a chaotic internal seismic character.

The overlying Utsira Formation (2) comprises a thick lower part of mainly quartzose sand, and a thinner upper part of glauconitic sand. The lower part is not present in any of the studied wells, but preliminary results from a study of this almost totally fossil-barren unit in well 35/11-1 (Fig. 1) indicate a Late Miocene to possible latest Middle Miocene age. It is thickest in the east and thins westwards towards the Tampen area (Fig. 2). The areal extent of the lower sand is shown in Fig. 1. The upper glauconitic part of the Utsira Formation (Late

Miocene-earliest Early Pliocene in age) is present in the Tampen wells. It is not clearly resolved on seismic sections, but is readily defined on wireline logs. It is about 15 m thick in block 34/4 and up to 50 m thick in block 34/8. In Fig. 2, the glauconitic part is shown overlying the Lower Miocene deposits in Visund well 34/8-3A and the Oligocene deposits in Snorre well 34/7-1. It may drape over, or may partly interfinger with the main Utsira Formation sands. The top of the Utsira Formation is defined on seismic in the east by the noticeable downlap of Upper Pliocene clinoforms. To the west, the transition to the overlying glauconitic sands and the basal Upper Pliocene sequence can be identified by a strong seismic event. To the north and northeast, the Utsira Formation sands were removed by erosion during the Pliocene, but time-equivalent sequences are probably present to the west of the Agat area (Fig. 1) and along the Møre margin (Y. Rundberg, personal observation).

In the Tampen area, a distinct seismic sequence (3) is identified at the base of the prograding Upper Pliocene complex. It is about 70 m thick in the Snorre wells and pinches out towards the east and west. The sequence is interpreted to consist of lowstand gravity deposits, laid down at the head of the prograding complex during an early phase of development.

The extensive incised valley/canyon system shown in Fig. 1 is an important feature of the Neogene strata of the northern North Sea. The system incises into the Oligocene deposits in the eastern part of the basin over an extensive area. As shown in Fig. 3, the incision postdates the basal Upper Pliocene sequence seen in well 34/2-4 (see discussion).

The Upper Pliocene complex is characterised by thick, westward prograding clinoforms (4). The base of the prograding complex is defined by the termination of downlap reflections against the underlying surface. In the Tampen area a thickness of up to 700 ms (approximately 650 m) is recorded. The Upper Pliocene strata comprise a number of individual sequences that prograde in a northwesterly direction. These are separated by several truncation surfaces, three of which are shown in Fig. 2. The lowermost truncation surface is only partly preserved. The middle truncation surface is the most pronounced and can be mapped across the entire northern North Sea. At certain locations in the eastern part of the northern North Sea, the Upper Pliocene strata rest directly on Oligocene sediments (Fig. 2).

The Pleistocene sequence (5) is identified below the seafloor with its prominent lower boundary showing distinct onlap reflection terminations above and toplap truncations below. The seismic sequence attains a thickness of about 200 m close to the Norwegian margin, as seen in well 31/3-1 (Fig. 1), and thins to a few tens of metres in the Tampen area.

Material and methods

In most of the studied wells, the biostratigraphic analyses were performed largely on ditch cutting samples. Sidewall cores were available in wells 34/4-7 (12 cores) and 34/7-1 (14 cores). In wells 34/8A-1H and 34/8-9S the work is based on material from cored sections in the base Upper Pliocene.

In general, no samples have been available from shallower than about 100 m below the seafloor. Consequently the Pleistocene section is not sampled in the Snorre and Visund fields. However, this section is investigated in well 31/3-1 in the Troll Field and by Sejrup et al. (1995). In wells 34/2-4, 34/4-7, 34/7-1 and 34/8-3A the work started in the lower part of the Upper Pliocene strata. Samples from the upper part of the Upper Pliocene deposits were not used. Ditch cuttings are usually sampled at 10 m intervals in upper Cainozoic sections. All the available samples were analysed, with the exception of some of the thicker units where intervals of 20-30 m were chosen (Tables 1 and 2).

The samples were analysed primarily for planktonic and benthic foraminifera. Reworked *Bolboforma* (calcareous cysts) were recorded in the Upper Miocene and Upper Pliocene sections in several wells. Pyritised diatoms were used to establish the stratigraphy in Lower Miocene and Oligocene deposits.

Between 50 and 100 g of material were used to analyse conventional core samples and cuttings. Sidewall cores contain less sample material, and thus produce incomplete, non-representative faunal assemblages. Sidewall core and conventional core analyses do, however, provide useful *in situ* assemblages, because the material is generally not contaminated by cavings.

Fossil identifications were performed in the 106-500 μm fraction. In some cases the fraction larger than 500 μm and the fraction less than 106 μm were also studied. If possible, 300 individual fossils were picked from each sample. In order to optimise identification of the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity-separated in heavy liquid. In such cases, 1000-1500 individuals were analysed in fossil rich samples. The stratigraphically important fossils are reported in the range charts in Figs. 5-13. For wells 34/4-7 and 34/7-1 separate range charts for fossils recorded in ditch cutting samples and those recorded in sidewall cores are presented. The range charts for the sidewall cores in wells 34/4-7 and 34/7-1, and those for the cored sections in wells 34/8A-1H and 34/8-9S, show all the fossils recorded.

The lithologic analyses are based on a visual examination both of the samples prior to treatment, and also of the dissolved and fractionated material after preparation. Owing to problems caused by caved material, only a very generalised description was deemed appropriate for most sections. However, the sidewall cores in wells 34/4-7 and 34/7-1 and the short conventional cores in wells 34/8A-1H and 34/8-9S allowed more accurate lithologic descriptions of these parts. These samples are of crucial importance to the reconstruction of the basin history.

Strontium isotope analyses were performed on parts of sections in most wells. Analysis was conducted mainly on tests of calcareous foraminifera, but mollusc fragments were also utilised in some wells. The material was taken mainly from sidewall and conventional cores, but ditch cutting samples were also used. Ages for these samples were obtained by comparing the ^{87}Sr/^{86}Sr-ratio to the global strontium isotope curves of Farrell et al. (1995) and Howarth and McArthur (1997).

Lithology, lithostratigraphy and log correlations

A lithostratigraphic log correlation of the studied wells is presented in Fig. 4.

The Lower-Upper Oligocene strata of the Hordaland Group represents the oldest sediments sampled in the Tampen wells. In the Snorre wells (blocks 34/4 and 34/7), there is an abrupt change in lithology at about 1150-1200 m, and the Oligocene deposits can readily be distinguished from the overlying strata by a change in colour and mineral composition. The upper part of the section displays a weakly serrated, low gamma log profile in all wells (Fig. 4). Oligocene sediments consist primarily of silty mudstones at the top, and are characterised by a brown to yellow colour and the ubiquitous presence of sponge spicules and glauconite. The microflora is dominantly siliceous, but small amounts of calcareous microfossils are also recorded.

In the Visund area (block 34/8), the Oligocene deposits are overlain by Lower Miocene sediments of the Hordaland Group (unit 1) which attain thickness of almost 100 m in well 34/8-3A. The log responses show a stable, weakly serrated pattern which indicates uniform lithology. The upper boundary is defined by an abrupt increase in both gamma radiation and sonic velocities (Fig. 4). Lithologically, these sediments are very similar to the Oligocene deposits with common glauconite and a rich siliceous flora. Calcareous microfossils are largely absent.

Overlying the Oligocene strata, a 15 m thick, highly radioactive unit 2 is clearly distinguished in the three Snorre wells 34/7-1, 34/4-7, 34/4-6. We propose that this unit is part of the Utsira Formation, and probably represents an upper glauconitic part of this formation. The transition from the underlying Oligocene sediments is marked by an abrupt change to higher gamma and sonic values (Fig. 4). In the Snorre wells, gamma radiation decreases towards the top of the unit, which is also defined by marked changes in the sonic and gamma log responses.

The unit expands eastwards to about 50 m in Visund wells 34/8-1 and 34/8-3A. The upper boundary is less well defined in this area, but is taken at a pattern change in the velocity logs. The gamma radiation is also lower than in the Snorre wells (Fig. 4). Sidewall cores taken from this unit in wells 34/4-7 and 34/7-1 contain almost exclusively glauconitic sand, which explains the high gamma radiation in the Snorre area, and suggests that the entire interval consists of such sediments. Slightly lower gamma levels and a greater thickness in the Visund wells probably indicate a lower glauconite content than is observed in the wells to the west. However, ditch cutting samples from these sections are also rich in glauconitic sand. The glauconite grains vary in shape and vary in their green colouration from dark to light. The dark fractions are indicative of high maturity and a high content of K_2O (Smalley & Rundberg 1990). The samples contain fair amounts of microfossils, comprising mostly calcareous benthic foraminifera and sponge spicules.

The basal Upper Pliocene unit of the Nordland Group (unit 3) is distinguished from the overlying and the underlying units by its characteristic monotonous gamma and sonic log profile. This is best illustrated in the Snorre wells, where the sonic logs clearly display a more serrated profile than in the units above and below (Fig. 4). The upper boundary is defined by an abrupt increase in gamma and sonic values. This is particularly marked in wells 34/7-1 and 34/4-7. The thickness of the unit is relatively uniform in blocks 34/4 and 34/7 (65-75 m).

Towards the east in the Visund area, the unit expands to about 100 m in well 34/8-1 and to 145 m in well 34/8-9S. In wells 34/8-1 and 34/8-A-1H, repeated cycles of increasing gamma radiation at intervals of 5-10 m are recorded. These probably reflect a series of small scale coarsening-upward units. In well 34/8-A-1H, about 11 m of core was recovered from a 30 m interval from the lower part of the unit (Fig. 4). The lithology encountered in the core is dominantly a very fine sandy siltstone throughout with a fine sandstone at the base. The sands are generally structureless, although faint laminations have been observed in the siltstones. The gamma log indicates that the cores have most likely been taken in the fine-grained sections. Three large (up to 5 cm) and several small ice-rafted pebbles of metamorphic rock have been found at different levels in the core. Coarse fragments of coal and small mud clasts also occur at some levels. At the base there is a diffuse transition to fine-grained, structureless sand.

In well 34/8-9S, a 4 m long core was recovered from the base of the unit. This core consists mainly of homogeneous, silty mudstone. Large (5-10 cm), mud clasts occur scattered throughout the core, and ice-rafted pebbles are common. The mud clasts mainly exhibit a shallow marine foraminiferal fauna in contrast to the deeper shelf fauna which is present elsewhere in the unit. The sediments in the two cores are interpreted as gravity flow deposits with a glacio-marine imprint.

The prograding Upper Pliocene complex of the Nordland Group (unit 4) reaches a maximum thickness of about 700 m in the Tampen area. Log responses are characterised by fairly stable patterns throughout, and commonly show higher gamma levels than the underlying sediments. The relatively high radioactive character of the Upper Pliocene deposits are most likely the result of the high potassium content of the sediments with abundant illite and K-feldspar (Rundberg 1989). The dominant lithology consists of immature, poorly sorted and sand-poor clastics. Sands are rare in the Tampen wells, with the exception of a 20 m thick interval at the base of the unit (Fig. 4). This interval consists of two blocky sand bodies separated by a thinner mudstone. It can be correlated between all of the Snorre wells in this study, and is interpreted as the eastern extension of thicker sands that occur in wells further to the west (Fig. 2). The sands in well 34/2-4 occur at an equivalent stratigraphic position and are most likely the same as those of the Snorre wells.

According to Rundberg (1989), the coarser constituents include quartz, plagioclase, K-feldspar, epidot, amphiboles and rock fragments (chiefly gneissose and granitic). Glauconites are rare, but shell debris is occasionally observed. The clay mineralogy also differs markedly from the underlying Miocene and Oligocene units. Illite and chlorite are most abundant, but smectite and kaolinite are also present.

In well 31/3-1 on the Troll field, the Pleistocene (unit 5) can be distinguished from the underlying Oligocene sediments by abrupt wireline log changes. The lithology of this unit is very similar to that of the Upper Pliocene, reflecting deposition in a partly glacial environment. A detailed lithologic description based on shallow cores from a geotechnical borehole near well 31/3-1 has been presented by Sejrup et al. (1995).

Biostratigraphic correlation

The standard Cainozoic biostratigraphic zonation is based on planktonic foraminifera and calcareous nannoplankton and is established for tropic and subtropic areas. In northern latitudes, the assemblages become progressively less diverse, and many key species are absent in the North Sea (King 1983).

In this study the fossil assemblages are correlated primarily with the biozonation of King (1983, 1989), who outlines a micropalaeontological zonation for Cainozoic sediments in the North Sea. Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken, the zonation by Stratlab (1986) and the work of Eidvin et al. (1998) are also used extensively. In addition, a number of articles describing benthic foraminifera from onshore basins in the area surrounding central and southern North Sea are utilised. The zonations of planktonic foraminifera (Weaver 1987, Weaver & Clement 1986, 1987, Spiegler & Jansen 1989) and *Bolboforma* (Spiegler & Müller 1992, Müller & Spiegler 1993) from ODP and DSDP drillings in the Norwegian Sea and the North Atlantic are also very important for the dating of the sediments. Correlation with these zones yields the most accurate age determinations, because the zones are calibrated with both nannoplankton and palaeomagnetic data. The zonations of King (1983, 1989) and Gradstein & Bäckström (1996) are based on the last appearance datums (LADs) of the various taxa. The planktonic foraminifera and *Bolboforma* zonations from the ODP and DSDP drillings are based on first appearance datums (FADs).

Fossil assemblages

In the nine wells examined in this study a system of eleven fossil assemblages is devised (N-A to N-G; Figs. 5-13). These stratigraphical units are informally designated as assemblages and are regarded as informal zones. This designation is preferred because the stratigraphy of the region seems not yet mature for introduction of a detailed, formal zonal scheme. The boundaries between the assemblages are based on the last appearance datums (LADs) of selected taxa which mostly have been chosen because of their chronostratigraphic importance. Most of the selected taxa have well-documented, consistent ranges on a regional scale. The individual assemblages comprise both planktonic and benthic forms. Fossil assemblages based on a combination of planktonic and benthic forms are applicable on a regional scale where planktonic/benthic ratios are often highly variable. The assemblages are described from top to base of the successions, following the order in which they are normally encountered in offshore borehole studies. Abbreviation of the assemblage designation are: N = northern North Sea.

WELL 31/3-1

NONION LABRADORICUM - NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) ASSEMBLAGE

Designation: N-A.

Definition: The top of the assemblage extends to the uppermost investigated sample (430 m). The base is marked by the highest occurrence of *Turrilina alsatica*.

Depth range: 430-540 m

Material: Eleven ditch cutting samples at 10 m intervals.

Age: Pleistocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzone NSB 16x of King (1989), Zone NSR 13 of Gradstein & Bäckström (1996) and *Neogloboquadrina pachyderma* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. *Elphidium excavatum, Bulimina marginata, Nonion affine, Cassidulina teretis, Islandiella norcrossi* and *N. labradoricum* occur most frequently. Other important species include *Cibicides lobatulus, Haynesina orbiculare, Angulogerina angulosa, Bolivina skagerrakensis, Islandiella helenae* and *Virgulina loeblichi* (Fig. 5).

Planktonic foraminifera are quite common, but less frequent than the benthic taxa. *N. pachyderma* (both encrusted and unencrusted varieties of sinistrally coiled individuals) is dominant. Other important species include *N. pachyderma* (dextral) and *Turborotalia quinqueloba.* A few specimens of *Globigerina bulloides* are also recorded.

Reworked assemblage: Reworked benthic calcareous and planktonic foraminifera from the Upper Cretaceous are recorded sporadically throughout the interval.

Remarks: All the benthic foraminifera here regarded as *in situ* are extant species typically associated with Pliocene-Pleistocene deposits of the Norwegian margin. *N. pachyderma* (sinistral, encrusted) has its first frequent occurrence at 1.8 Ma (Weaver & Clement 1986, Spiegler & Jansen 1989). This test morphology has only sporadic occurrences in older sediments. *N. labradoricum* also appears to be restricted to Pleistocene deposits on the Norwegian shelf. King (1989) employs *N. labradoricum* as the nominate taxa for the Pleistocene Subzone NSB 16x of the northern North Sea. This indicates a Pleistocene age for this interval. The lowermost part of the Pleistocene is probably not present. This is based on the fact that *C. grossus* and *E. hannai* are not recorded. According to King (1989) and Eidvin et al. (1999) the LADs of both these species are in early part of Early Pleistocene.

Sejrup et al. (1995) have investigated a cored geotechnical borehole, also from the Troll Field, near well 31/3-1. The borehole just penetrates the base Pleistocene angular unconformity. The cores from this borehole have been subjected to palaeomagnetic, amino acid and foraminiferal analyses. The base of the Pleistocene section in this borehole is dated to approximately 1.2 Ma by means of paleomagnetic polarity reversal chronology. A similar age is probable for the base of the N-A assemblage.

TURRILINA ALSATICA – GYROIDINA SOLDANII MAMILLATA – STILOSTOMELLA HIRSUTA ASSEMBLAGE

Designation: N-G

Definition: The top of assemblage is taken at the highest occurrence of *T. alsatica.* The base of the assemblage is not defined.

Depth range: 540-580 m.

Age: Early Oligocene.

Material: Four ditch cutting samples at 10-20 m intervals.

Lithostratigraphic group: Hordaland Group.

Correlation: Subzones NSB 7a or 7b of King (1989) and Zones NSR 7A or 7B of Gradstein & Bäckström (1996).

Assemblage: This interval contains a high diversity fauna of mainly calcareous benthic foraminifera. The most important taxa are *G. soldanii girardana* and *T. alsatica.* Other characteristic species include *Stilostomella longiscata, S. adolphina, S. hirsuta, Karreriella siphonella, Ceratobulimina contraria, G. soldanii mamillata, P. bulloides, Bulimina alsatica, Loxostomum digitale, Alabamina wolterstoffi* and *Alabamina tangentialis* (Fig. 5).

Remarks: *T. alsatica* and *G. soldanii girardana* are known from the Lower Oligocene to the lowermost Lower Miocene succession in the North Sea (King 1989). According to Gradstein & Bäckström (1996) these species are known from Lower Oligocene to lowermost Upper Oligocene deposits in the North Sea. *G. soldanii mamillata* is also known from Lower Oligocene to the lowermost Upper Oligocene strata from the same area (King 1989, Gradstein & Bäckström 1996). *L. digitale* and *A. wolterstoffi* are known from the Oligocene succession in Belgium (Batjes 1958) and *S. longiscata, S. adolphina, S. hirsuta, A. tangentialis* and *C. contraria* are recorded from the upper part of the Lower Oligocene succession in Denmark (Ulleberg 1974).

WELL 34/8-1

CIBICIDES GROSSUS - ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES - NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample (440 m). The base is marked by the highest occurrence of *Ehrenbergina variabilis*.

Depth range: 440-1090 m.

Material: 34 ditch cutting samples at 10-30 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *Neogloboquadrina atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. The fauna is relatively uniform throughout the entire section, but this observation is partly due to extensive caving. *E. excavatum* occurs most frequently. Other characteristic taxa include *Angulogerina fluens, Cibicides scaldisiensis, B. marginata, N. affine, C. grossus, E. hannai* and *Islandiella islandica* (upper and lower part; Fig. 6).

Planktonic foraminifera are also quite common, but less frequent than the benthic foraminifera. Important planktonic species include *G. bulloides, N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *Globorotalia inflata* (upper part) and *N. atlantica* (dextral; upper part). *T. quinqueloba* is scarce throughout.

Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary, benthic calcareous and planktonic foraminifera from the Upper Cretaceous and *Inoceramus* prisms from the Upper Cretaceous. At the base of the interval a few specimens of *Eponides pygmeus* and *Cibicides telegdi*, probably from the Miocene and *Bolboforma subfragori* from the Middle-Upper Miocene, are recorded.

Remarks: With the exception of *C. grossus* and *E. hannai* all the *in situ* benthic foraminifera are extant species. According to King (1989) *C. grossus* and *E. hannai* are found in the northern North Sea in Upper Pliocene to Lower Pleistocene deposits. FADs of these species are considerably higher than the Lower/Upper Pliocene boundary (3.56 Ma). *C. grossus* is, however, recorded in deposits as old as the late Middle Miocene on the Vøring Plateau (T. Eidvin, personal observation) and as old as the Late Miocene in the Netherlands. However, *E. hannai* is known from Upper Pliocene deposits in the latter area (Doppert 1980).

Only the unencrusted variety of sinistrally coiled *N. pachyderma* is recorded in this interval. The encrusted variety of this form is dominating the planktonic foraminiferal fauna in the Norwegian Sea after 1.8 Ma (Weaver & Clement 1986, Spiegler & Jansen 1989). The fact that this form is not recorded indicates that Pleistocene sediments are not sampled in this well. This is also supported by the fact that *Nonion labradoricum* is also missing in this assemblage. King (1989) use *N. labradoricum* as the nominate taxon for the Pleistocene Zone NSB 16x of the northern North Sea, and this taxa has been recognised in the Pleistocene section in well 31/3-1. However, Pleistocene sediments are probably present in parts of the 90 m unsampled section.

N. atlantica (dextral) is quite common in the upper part of this unit. This taxa is known from an upper *N. atlantica* (dextral) Zone which is described from the Vøring Plateau in Upper Pliocene deposits. LAD of this species is approximately 1.9 Ma in that area (Spiegler & Jansen 1989). On the Vøring Plateau the upper *N. atlantica* (dextral) Zone lies above a *N. atlantica* (sinistral) Zone. The *N. atlantica* (sinistral) Zone is also rich on *G. bulloides*, but *N. atlantica* (dextral) is scarce in this zone. LAD of *N. atlantica* (sinistral) is about 2.4 Ma on the

Vøring Plateau. In well 34/8-1 *N. atlantica* (dextral) occurs, quite numerously, together with *N. atlantica* (sinistral) and *G. bulloides*, and consequently seems to have a somewhat different occurrence than in the Norwegian Sea. The top of the N-B1 assemblage is probably close to 2.4 Ma.

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The base is marked by the highest occurrence of Diatom sp. 4 (King 1983) and Diatom sp. 5 (King 1983).

Depth range: 1090-1140 m.

Material: Five ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

In-place assemblage: There are slightly fewer microfossils in this interval than in the overlying interval. In this assemblage the benthic fauna includes calcareous foraminifera and sponge spicules. A few agglutinated foraminifera are also recorded. Sponge spicules (both rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. The most frequently occurring foraminifera are *A. fluens, C. teretis* and *N. affine*. Other important species include *E. variabilis, Pullenia bulloides, E. pygmeus* and *Globocassidulina subglobosa. C. telegdi* and *Martinottiella communis* (agglutinated) are also recorded at a few levels (Fig. 6).

Planktonic foraminifera include *G. bulloides* and *N. atlantica* (sinistral) which are dominant. Other species are *N. pachyderma (sinistral, unencrusted), N. atlantica (dextral), N. pachyderma* (dextral), *T. quinqueloba* and *G. inflata*.

Reworked assemblage: Presumed reworked *Bolboforma* from the uppermost Middle Miocene and lowermost Upper Miocene are recorded sporadically throughout and include *B. subfragori, B. metzmacheri, B. clodiusi, B. compressibadenensis, B. fragori* and *B. pseudohystrix.*

Remarks: Most of the benthic foraminifera are known from almost the entire Neogene succession. Some of these and some of the planktonic foraminifera are probably caved. *E. variabilis* is recorded from the Upper Oligocene to Lower Miocene of Germany (Grossheide & Trunco 1965, Spiegler 1974), from the Upper Miocene on the Norwegian Sea continental shelf (Stratlab 1986, Eidvin et al. 1998) and from the Upper Oligocene to Lower Pliocene on the Norwegian continental shelf (Skarbø & Verdenius 1986). *E. pygmeus* and *C. telegdi* are recorded from the Upper Oligocene and older deposits in Denmark and Germany (Grossheide & Trunko 1965, Hausmann 1964, Kummerle 1963 and Ulleberg 1974). On the Norwegian Sea continental shelf these species are known from Upper Miocene deposits according to Eidvin et al. (1998) and from Upper Miocene-Lower Pliocene deposits according to Stratlab (1986). *G. subglobosa* is known from the Middle to Upper Miocene of Belgium (Doppert 1980) and from the Upper Oligocene to Upper Miocene of Germany (Spiegler 1974). In the central North Sea *G. subglobosa* is recorded from Upper Oligocene to basal Upper Pliocene deposits (Eidvin et al. 1999), and on the Norwegian Sea continental shelf from Upper Miocene deposits (Stratlab 1986, Eidvin et al. 1998). *M. communis* is known from Middle to Upper Miocene deposits on the Vøring Plateau (Osterman & Qvale 1989).

N. atlantica (dextral) is known to occur in the uppermost Upper Pliocene and in the Upper Miocene on the Vøring Plateau (Spiegler & Jansen 1992, Müller & Spiegler 1993). Consequently, these can be caved from the overlying assemblage or they can be *in situ* Upper Miocene specimens.

DIATOM SP. 4 – DIATOM SP. 5 ASSEMBLAGE

Designation: N-E.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 4 and Diatom sp. 5. The base is marked by the highest occurrence of *Turrilina alsatica* and Diatom sp. 3 (King 1983).

Depth range: 1140-1170 m.

Material: Three ditch cutting samples at 10 m intervals.

Age: Early Miocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Description: The greater proportion of the fossils recorded in this interval are sponge spicules (both rod-shaped and *Geodia* sp.) and radiolarians. Far fewer pyritised diatoms are recorded. Most of the diatoms are Diatom sp. 4 and Diatom sp. 5 (Fig. 6).

Remarks: Diatom sp. 4 and Diatom sp. 5 are both known from Lower Miocene deposits in the North Sea (King 1983).

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-F1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and Diatom sp. 3. The base of the assemblage is undefined.

Depth range: 1170-1320 m (lowermost investigated sample).

Material: 10 ditch cutting samples at 10-20 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is also dominated by sponge spicules. Radiolarians and pyritised diatoms are also quite common. Far fewer benthic foraminifera, mainly calcareous but also some agglutinated forms, are recorded. In the diatom flora the index fossil Diatom sp. 3 is recorded. *T. alsatica* is the dominant foraminifer. Other characteristic foraminifera include *G. soldanii girardana, Trifarina gracilis, Eponides umbonatus* and *Trochammina* sp. *Rotaliatina bulimoides* and *G. soldanii mamillata* are also recorded at two levels (Fig. 6).

Remarks: *T. gracilis* is recorded from Lower Oligocene to Lower Miocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986). Diatom sp. 3 is known from uppermost Lower Oligocene to lowermost Lower Miocene deposits in the North Sea (King 1989). According to King (1989) *T. alsatica* and *G. soldanii girardana* are also known from Lower Oligocene to lowermost Lower Miocene sediments in the same area. According to Gradstein & Bäckström (1996) are these species known from Lower Oligocene to lowermost Upper Oligocene deposits in the North Sea. *G. soldanii mamillata* is known from the Lower Oligocene to the lowermost Upper Oligocene from the same area (King 1989, Gradstein & Bäckström 1996). *R. bulimoides* is known from the Lower Oligocene to the lowermost Upper

Oligocene according to King (1989) and from the Lower Oligocene according to Gradstein & Bäckström (1996).

WELL 34/8-9S

CIBICIDES GROSSUS – ELPHIDIUM ALBIUMBILICATUM – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B2.

Definition: The top of the assemblage extends to the uppermost investigated sample. The base extends to the lowermost investigated sample.

Depth range: 1109.68-1112.63 m.

Material: Four conventional core samples.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. The fauna varies considerably throughout this short section. *N. affine, C. lobatulus, C. teretis* and *E. excavatum* occur most frequently throughout the assemblage. *B. marginata, A. fluens* and *Loxostomoides lammersi* also appear consistently throughout. *E. albiumbilicatum, C. grossus* and *Elphidium groenlandicum* are common in parts of the interval. *Cibicidoides pachyderma*, *C. scaldisiensis*, *Elphidium bartletti* and *Sigmoilosis schlumbergeri* (agglutinated) are also found in parts of the section (Fig. 7).

Planktonic foraminifera are less frequent than benthic taxa. *G. bulloides* and *N. atlantica* (sinistral) are dominant. *Globigerinita glutinata, N. atlantica* (dextral) and *T. quinqueloba* occur sporadically.

Reworked assemblage: Reworked foraminifera are recorded sporadically. These are *E. pygmeus* from Miocene deposits, *Uvigerina pygmea langeri* from the Upper Miocene, *Bolboforma laevis, B. clodiusi, B. subfragori* and *B. fragori* from the Middle-Upper Miocene. A few specimens of *Heterohelix* sp. and *Inoceramus* prisms from the Upper Cretaceous are also recorded.

Remarks: According to King (1989) FADs of *C. grossus, E. albiumbilicatum* and *E. groenlandicum* are in the late part of Late Pliocene in the North Sea area. However, the occurrence of *N. atlantica* (sinistral) indicates an age no younger than 2.4 Ma (Spiegler & Jansen 1989).

WELL 34/8A-1H

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERIA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample. The base extends to the lowermost investigated sample.

Depth range: 1070.2-1102 m.

Material: Seven conventional core samples.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of calcareous foraminifera. The fauna varies considerably throughout this short section. *N. affine, C. lobatulus, C. teretis* all occur frequently throughout the interval. *C. grossus, E. hannai, E. albiumbilicatum, E. excavatum, A. fluens and Buccella tenerrima* are recorded in the middle part of the unit (Fig. 8).

Planktonic foraminifera are less frequent than benthic taxa, but these are also quite common in parts of the interval. *G. bulloides* and *N. atlantica* (sinistral) are dominant. *T. quinqueloba, N. pachyderma* (dextral) and *N. atlantica* (dextral) occur sporadically.

Reworked assemblage: Reworked foraminifera are recorded sporadically. These are *C. telegdi*, from Miocene deposits and *T. alsatica and G. soldanii girardana* from the Oligocene.

Remarks: The occurrence of *C. grossus, E. hannai, E. albiumbilicatum, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

WELL 34/8-3A

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample (1000 m). The base is marked by the highest occurrence of *E. variabilis.*

Depth range: 1000-1110 m.

Material: Eleven ditch cutting samples at 10 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This assemblage contains a rich benthic fauna of calcareous foraminifera. The fauna is relatively uniform throughout the interval, but this is probably partly due to extensively caved material. *N. affine, A. fluens, C. teretis* and *C. grossus* occur most frequently. Other characteristic taxa include *C. lobatulus, E. hannai, Buccella tenerrima, E. excavatum, Cassidulina reniforme and I. islandica* (lower part; Fig. 9).

Planktonic foraminifera are less frequent than the benthic taxa. *G. bulloides* and *N. pachyderma* (dextral) are dominant. Other important species include *T. quinqueloba* and *N. atlantica* (sinistral; lower part). *N. pachyderma* (sinistral) and *G. glutinata* occur sporadically.

Remarks: The occurrence of *C. grossus, E. hannai, E. albiumbilicatum, N. atlantica* (sinistral) and *G. bulloides* indicate a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The highest occurrence of *Eponides umbonatus*, *Stilostomella* sp. and the highest abundant occurrence of diatoms mark the base of the assemblage.

Depth range: 1110-1180 m.

Material: Seven ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on log correlation).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

In-place assemblage: There are slightly fewer microfossils in this interval than in the overlying assemblage. In this interval the benthic fauna is dominated of calcareous foraminifera and sponge spicules. A few agglutinated foraminifera are also recorded. The most frequently occurring foraminifera are *Cibicides dutemplei, C. teretis* and *N. affine* (upper part). Other characteristic taxa include *E. variabilis, A. fluens, E. pygmeus, P. bulloides, Uvigerina pygmea langeri, G. subglobosa* and *M. communis* (agglutinated; Fig. 9).

Far fewer planktonic than benthic foraminifera are recorded. Planktonic forms include *G. bulloides, N. pachyderma* (dextral), *T. quinqueloba, N. atlantica* (sinistral), *G. glutinata* and *N. atlantica* (dextral).

Reworked assemblage: A few specimens of presumed reworked *Bolboforma* from the uppermost Middle Miocene and lowermost Upper Miocene are recorded and *include B. metzmacheri, B. fragori* and *B. clodiusi.*

Remarks: *U. pygmea langeri* is described from Upper Miocene deposits of the North Sea (King 1989). *C. dutemplei* is known from the Upper Eocene to Middle Miocene of Belgium (Kaasschieter 1961, Skarbø & Verdenius 1986), from Upper Eocene to Lower Pliocene deposits in the Netherlands (Doppert 1980) and from Upper Oligocene to Upper Miocene sediments on the Norwegian continental shelf (Skarbø & Verdenius 1986).

This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/2-4, 34/4-6, 34/4-7 and the N-C2 assemblage in well 34/7-1.

EPONIDES UMBONATUS – STILOSTOMELLA SP. – DIATOM SP. ASSEMBLAGE

Designation: N-D.

Definition: The top of the assemblage is taken at the highest occurrence of *E. umbonatus* and *Stilostomella* sp. and the highest abundant occurrence of diatoms. The base is marked by the highest occurrence of Diatom sp. 5.

Depth range: 1180-1210 m.

Material: Three ditch cutting samples at 10 m intervals.

Age: Early Miocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Probably Zone NSP 10 of King (1983).

Description: The greater proportion of the fossils recorded in this interval are diatoms, radiolarians and sponge spicules (both rod-shaped and *Geodia* sp.). Far fewer foraminifera are recorded and most of these are probably caved. However, the calcareous benthic forms *E. umbonatus* and *Stilostomella* sp. are probably *in situ* (Fig. 9).

Remarks: It is difficult to determine the precise age of this assemblage. No short-range index fossils are recorded. *E. umbonatus* are known from deposits from the Eocene to recent (Kaasschieter 1961, Mackensen 1985). *Stilostomella* sp., the sponge spicules, the radiolarians and the diatoms give only a general Early Neogene to Late Palaeogene age. However, this assemblage is very similar to the immediately underlying, Early Miocene, Diatom sp. 4 and Diatom sp. 5 assemblage (N-E). Several of the pyritised diatoms are very similar to Diatom sp. 4 and Diatom sp. 5, but the projections near the valve margin of the specimens are smaller and not as equally spaced as on the Diatom sp. 4 and Diatom sp. 5 of King (1983). However, the diatoms probably descend from Diatom sp. 4 and Diatom sp. 5 and it is probable that the N-F assemblage also is of Early Miocene age.

DIATOM SP. 4 – DIATOM SP. 5 ASSEMBLAGE

Designation: N-E.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 5. The base is marked by the highest occurrence of *T. alsatica.*

Depth range: 1210-1240 m.

Material: Three ditch cutting samples at 10 m intervals.

Age: Early Miocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Zone NSP 10 of King (1983).

Description: Also this assemblage is completely dominated by diatoms, radiolarians and sponge spicules (both rod-shaped and *Geodia* sp.; Fig. 9). Just a few foraminifera are recorded and these are probably caved. Several of the diatoms are Diatom sp. 4 and Diatom sp. 5.

Remarks: Diatom sp. 4 and Diatom sp. 5 are both known from Lower Miocene deposits in the North Sea (King 1983).

TURRILINA ALSATICA ASSEMBLAGE

Designation: N-F2.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica*. The base of the assemblage is undefined.

Depth range: 1240-1300 m (lowermost investigated sample).

Material: Six ditch cutting samples at 10-20 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzone NSB 8a and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is also dominated by diatoms, radiolarians and sponge spicules. Far fewer foraminifera are recorded. Some of these are probably caved, but *in situ* forms include *T. alsatica, G. soldanii girardana, T. gracilis* and *Nonion* sp. A (King 1989) (Fig. 9).

Remarks: *Nonion* sp. A is recorded from Lower Oligocene to Lower Miocene deposits in the North Sea (King 1989).

This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, 34/7-1 and the N-F3 and N-F4 assemblages in well 34/2-4.

WELL 34/4-6

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample (540 m). The base is marked by the highest occurrence of *E. variabilis*.

Depth range: 540-1210 m.

Material: 34 ditch cutting samples at 10-30 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This assemblage contains a rich benthic fauna of mainly calcareous foraminifera. The upper and lower parts of the assemblage contain more specimens than the middle part. The fauna is relatively uniform throughout, but this observation is partly due to extensive caving. *E. excavatum* and *C. teretis* occur most frequently. Other important species include *E. hannai, B. marginata, Cibicides lobatulus*, *C. grossus, E. albiumbilicatum, B. tenerrima, H. orbiculare, C. scaldisiensis, Uvigerina mediterranea* (upper part), *N. affine* (upper and lower part) and *I. islandica* (upper and lower part).

Planktonic foraminifera are also less common in the middle part of the interval. They are overall less frequent than benthic taxa and include *N. atlantica* (sinistral), *G. bulloides, N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *G. Inflata, N. atlantica* (dextral) and *T. quinqueloba* (scarce throughout; Fig. 10).

Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary and benthic calcareous and planktonic foraminifera from the Upper Cretaceous. At the base of the assemblage *C. dutemplei*, *E. pygmeus* and *C. telegdi* are recorded at some levels. These are probably reworked from Miocene deposits.

Remarks: The occurrence of *C. grossus, E. hannai, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989). Pleistocene sediments are probably present in parts of the 140 m unsampled section.

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The base is marked by the highest occurrence of *T. alsatica* and Diatom sp. 3.

Depth range: 1210-1250 m.

Material: Four ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone

(M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

Description: There are slightly fewer foraminifera in this interval than in the lower part of the overlying interval. In addition, specimens of sponge spicules (both rod-shaped and *Geodia* sp.) are common in this assemblage. The most important benthic calcareous species are *N. affine* and *C. teretis*. Other species include *A. fluens, E. variabilis, P. bulloides, E. pygmeus, C. telegdi* and *C. dutemplei* (Fig. 10). Some of these are probably caved.

Planktonic foraminifera are less frequent than the benthic taxa and include *G. bulloides, N. atlantica* (sinistral), *G. inflata, N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *N. atlantica* (dextral) and *T. quinqueloba*. Some of these are also probably caved.

Remarks: This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/2-4, 34/4-7 and the N-C2 assemblage in well 34/7-1.

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-F1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and Diatom sp. 3. The base of the assemblage is undefined.

Depth range: 1250-1370 m (lowermost investigated sample).

Material: Nine ditch cutting samples at 10-20 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is dominated by sponge spicules, radiolarians and bryozoan fragments. Far fewer benthic calcareous foraminifera and pyritised diatoms are recorded. In the diatom flora the index fossil Diatom sp. 3 occurs consistent throughout. *T. alsatica*, *G. soldanii girardana* and *T. gracilis* are the dominant foraminifera. Several specimens of *G. soldanii mamillata* and *R. bulimoides* are also recorded at a few levels (Fig. 10).

Remarks: This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-7, 34/7-1, the N-F2 assemblage in well 34/8-3A and the N-F3 and N-F4 assemblages in well 34/2-4.

WELL 34/4-7

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Description: The top of the assemblage extends to the uppermost investigated sample (1000 m). The base is marked by the highest occurrence of *E. variabilis*.

Depth range: 1000-1180 m.

Material: Nine sidewall cores and 18 ditch cutting samples at 10 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This assemblage contains a rich benthic fauna of mainly calcareous foraminifera. *E. excavatum*, *C. teretis* and *C. grossus* (lower part) occur most frequently. Other important species include *Islandiella helenae*, *C. lobatulus*, *E. hannai*, *B. marginata*, *H. orbiculare*, *C. scaldisiensis*, *B. tenerrima*, *I. islandica* and *N. affine* (lower part) (Figs. 11a and b).

Planktonic foraminifera are less frequent than benthic taxa and include *N. atlantica* (sinistral), *G. bulloides*, *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral) and *G. inflata*. *T. quinqueloba* and *N. atlantica* (dextral) are also recorded at a few levels.

Reworked assemblage: Reworked fossils are recorded sporadically in the lower part of the assemblage. These are *C. dutemplei*, *E. pygmeus* and *C. telegdi* from Miocene deposits, *Inoceramus* prisms from the Upper Cretaceous and Diatom sp. 3 from the Oligocene.

Remarks: The occurrence of *C. grossus, E. hannai, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The base is marked by the highest occurrence of *T. alsatica* and the highest consistent occurrence of Diatom sp. 3.

Depth range: 1180-1200 m.

Material: Two sidewall cores and two ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

In-place assemblage: There are slightly fewer foraminifera in this interval than in the overlying assemblage. In addition specimens of sponge spicules (both rod-shaped and *Geodia* sp.) are common in this interval. Many foraminifera, which are recorded in the ditch cutting samples (Fig. 11b), are not recorded in the sidewall cores samples (Fig. 11a), and most of these are probably caved. The following benthic foraminifera are probably *in situ*: *C. teretis, N. affine, E. variabilis, P. bulloides, E. pygmeus, C. telegdi* and *C. dutemplei*. *N. atlantica* (sinistral), *N. atlantica* (dextral) and *G. bulloides* are probably *in situ* planktonic foraminifera.

Reworked assemblage: *T. gracilis* is probably reworked from Lower Oligocene-Lower Miocene deposits and Diatom sp. 4 is probably reworked from Lower Miocene sediments.

Remarks: This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/2-4, 34/4-6 and the N-C2 assemblage in well 34/7-1.

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-E1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and the highest consistent occurrence of Diatom sp. 3. The base of the assemblage is not defined.

Depth range: 1200-1220 m (lowermost investigated sample).

Material: One sidewall core and three ditch cutting samples at 10 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: Sponge spicules and radiolarians dominate the fossil assemblage in this interval. Far fewer planktonic and benthic calcareous foraminifera and pyritised diatoms are recorded. The sidewall core sample contains only sponge spicules and diatoms (Fig. 11a). The planktonic foraminifera and several of the benthic calcareous forms are probably caved, but the following benthic forms are probably *in situ*: *T. alsatica*, *G. soldanii girardana*, *C. dutemplei* and *Guttulina* sp. (Fig. 11b).

Remarks: This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6 and 34/7-1, the N-F2 assemblage in well 34/8-3A and the N-F3 and N-F4 assemblages in well 34/2-4.

Well 34/7-1

CIBICIDES GROSSUS - ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample. The base is marked by the highest consistent occurrence of *C. dutemplei*.

Depth range: 1000-1150 m.

Material: 12 sidewall cores and 15 ditch cutting samples at 10 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. *E. excavatum*, *C. teretis* and *N. affine* occur most frequently. Other important species include *C. lobatulus*, *E. hannai*, *B. marginata*, *A. fluens*, *C. grossus*, *C. scaldisiensis* and *I. islandica* (lower part) (Figs. 12a and b).

Planktonic foraminifera are less frequent than benthic taxa and include *N. atlantica* (sinistral), *G. bulloides*, *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *N. atlantica* (dextral; scarce) and *G. inflata* (scarce).

Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary and *C. dutemplei* from Miocene deposits.

Remarks: The occurrence of *C. grossus, E. hannai, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

CIBICIDES DUTEMPLEI ASSEMBLAGE

Designation: N-C2.

Definition: The top of the assemblage is taken at the highest consistent occurrence of *C. dutemplei*. The base is marked by the highest occurrence of *T. alsatica* and Diatom sp. 3.

Depth range: 1150-1170 m.

Material: Two sidewall cores and two ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on log correlation).

Lithostratigraphic formation: Utsira Formation.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

Assemblage: There are slightly fewer foraminifera in this assemblage than in the overlying interval. In addition, specimens of sponge spicules and radiolarians are common. Calcareous foraminifera are only recorded in the ditch cutting samples (Fig. 12b) and most of these are probably caved. The small sidewall core samples contain only sponge spicules and agglutinated foraminifera (Fig. 12a), but the following benthic foraminifera are probably *in situ*: *C. dutemplei, C. teretis, N. affine, E. pygmeus, C. telegdi and Trochammina quinqueloba* (agglutinated). *N. atlantica* (sinistral) and *G. bulloides* are probably *in situ* planktonic foraminifera.

Remarks: Although *E. variabilis* is not recorded in any of the samples, the assemblage is correlated with the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/4-6, 34/4-7 and 34/2-4. However, *E. variabilis* are recorded in the uppermost sample in the immediately underlying assemblage, and are probably caved from this interval.

TURRILINA ALSATICA - DIATOM SP. 3 ASSEMBLAGE

Designation: N-F1.

Definition: The top of the assemblage is taken at the highest occurrence of *T. alsatica* and *G. soldanii girardana*. The base of the assemblage is not defined.

Depth range: 1170-1200 m (lowermost investigated sample).

Material: Four ditch cutting samples at 10 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzones NSB 8a and NSP 9c and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: There are fewer foraminifera in this assemblage than in the overlying interval. The assemblage contains radiolarians, diatoms and calcareous foraminifera. In the diatom flora the index fossil Diatom sp. 3 is recorded. The planktonic foraminifera and several of the benthic calcareous forms are probably caved, but the following benthic foraminifera are probably *in situ*: *T. alsatica*, *T. gracilis*, *G. soldanii girardana*, *R. bulimoides and C. dutemplei* (Fig. 12b).

Remarks: This assemblage is coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, the N-F2 assemblage in well 34/8-3A and the N-F3 and N-F4 assemblages in well 34/2-4.

WELL 34/2-4

CIBICIDES GROSSUS – ELPHIDIELLA HANNAI – GLOBIGERINA BULLOIDES – NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ASSEMBLAGE

Designation: N-B1.

Definition: The top of the assemblage extends to the uppermost investigated sample (1300 m). The base is marked by the highest occurrence of *E. variabilis.*

Depth range: 1300-1470 m.

Material: 16 ditch cutting samples at 10-20 m intervals.

Age: Late Pliocene.

Lithostratigraphic group: Nordland Group.

Correlation: Subzones NSB 15a of King (1989) and *N. atlantica* (sinistral) Zone of Spiegler & Jansen (1989).

In-place assemblage: This interval contains a rich benthic fauna of mainly calcareous foraminifera. *C. teretis* occurs most frequently. Other important species include *C. grossus, E. hannai, B. marginata, A. fluens, B. tenerrima, C. scaldisiensis, Quinqueloculina seminulum* and *E. excavatum.*

Planktonic foraminifera are also quite common, but less frequent than the benthic taxa. The most important planktonic foraminifera include *G. bulloides*, *N. atlantica* (sinistral), *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral). *N. atlantica* (dextral) and *T. quinqueloba* are recorded as rare at a few levels (Fig. 13).

Reworked assemblage: Reworked fossils are recorded sporadically throughout. These are agglutinated foraminifera from the lower Tertiary and *Inoceramus* prisms from the Upper Cretaceous. At the base of the interval *C. dutemplei*, *G. subglobosa*, *E. pygmeus*, *C. telegdi* and *T. alsatica* are recorded at some levels. *C. dutemplei*, *G. subglobosa*, *E. pygmeus* and *C. telegdi* are probably reworked from the Miocene and *T. alsatica* from the Oligocene.

Remarks: The occurrence of *C. grossus, E. hannai, N. atlantica* (sinistral) and *G. bulloides* indicates a Late Pliocene age no younger than 2.4 Ma (King 1989, Spiegler & Jansen 1989).

EHRENBERGINA VARIABILIS ASSEMBLAGE

Designation: N-C1.

Definition: The top of the assemblage is taken at the highest occurrence of *E. variabilis*. The base is marked by the highest occurrence of *G. soldanii girardana*.

Depth range: 1470-1520 m.

Material: Five ditch cutting samples at 10 m intervals.

Age: Late Miocene to earliest Early Pliocene (partly based on strontium isotope analysis).

Lithostratigraphic group: Nordland Group.

Correlation: Lower *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989), *G. subglobosa - E. variabilis* Zone of Stratlab (1986), *C. telegdi – E. pygmeus – N. atlantica* (dextral) Zone (M-H) and *E. variabilis - G. subglobosa - N. atlantica* (dextral) Zone (M-I) of Eidvin et al. (1998).

Description: There are slightly fewer foraminifera in this assemblage than in the lower part of the overlying assemblage. In addition, specimens of sponge spicules (rod-shaped and *Geodia* sp.) are common in this assemblage. The most important benthic calcareous foraminifera include *E. variabilis, E. pygmeus, C. dutemplei, C. telegdi, C. teretis* and *N. affine*. A few specimens of *G. subglobosa* are also recorded. Some of these and a few of the other recorded species (Fig. 13) are probably caved.

Planktonic foraminifera are less frequent than in the immediately overlying interval. *N. atlantica* (sinistral) and *G. bulloides* occur most frequently. *N. atlantica* (dextral), *T.*

quinqueloba and *G. inflata* are also recorded at a few levels. Some of these are also probably caved.

Remarks: This assemblage corresponds to the N-C1 assemblage in wells 34/8-1, 34/8-3A, 34/4-6, 34/4-7 and the N-C2 assemblage in well 34/7-1.

GYROIDINA SOLDANII GIRARDANA ASSEMBLAGE

Designation: N-F3.

Definition: The top of the assemblage is taken at the highest occurrence of *G. soldanii girardana*. The base is marked by the highest occurrence of Diatom sp. 3.

Depth range: 1520-1550 m.

Material: Three ditch cutting samples at 10 m intervals.

Age: Early-Late Oligocene.

Lithostratigraphic group: Hordaland Group.

Correlation: Lower part of Subzone NSB 8a and upper part of Subzone NSB 7b of King (1989) and upper part of Zone NSR 7B of Gradstein & Bäckström (1996).

Description: The fossil assemblage in this interval is dominated by sponge spicules. Far fewer benthic foraminifera (mostly calcareous but also a few agglutinated forms), planktonic foraminifera, radiolarians and pyritised diatoms are recorded. The planktonic foraminifera and several of the benthic calcareous forms are probably caved, but the following benthic foraminifera are probably *in situ*: *C. dutemplei, G. soldanii girardana, T. gracilis, C. placenta* (agglutinated) and *Cribrostomoides* sp. (agglutinated) (Fig. 13).

Remarks: *T. gracilis* is recorded from Lower Oligocene to Lower Miocene deposits on the Norwegian continental shelf (Skarbø & Verdenius 1986). *G. soldanii girardana* is known from Lower Oligocene to lowermost Lower Miocene sediments in the North Sea (King 1989). According to Gradstein & Bäckström (1996) is *G. soldanii girardana* known from the Lower Oligocene to the lowermost Upper Oligocene in the same area. This assemblage is probably coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, 34/7-1 and the N-F2 assemblage in well 34/8-3A.

DIATOM SP. 3 ASSEMBLAGE

Designation: N-F4.

Definition: The top of the assemblage is taken at the highest occurrence of Diatom sp. 3. The base of the assemblage is not defined.
Depth range: 1550-1600 m (lowermost investigated sample).
Material: Six ditch cutting samples at 10 m intervals.
Age: Early-Late Oligocene.
Lithostratigraphic group: Hordaland Group.
Correlation: Lower part of Subzone NSP 9c of King (1989).
Description: The fossil assemblage in this interval is nearly completely dominated by sponge spicules (both rod-shaped and *Geodia* sp.), radiolarians and pyritised diatoms. In the diatom flora the index fossil Diatom sp. 3 is recorded (Fig. 13).
Remarks: This assemblage is probably coeval with the N-F1 assemblage in wells 34/8-1, 34/4-6, 34/4-7, 34/7-1 and the N-F2 assemblage in well 34/8-3A.

Strontium isotope stratigraphy

The strontium isotopic record of Neogene seawater is documented by Hodell et al. (1990, 1991) and Farrell et al. (1995). In order to better constrain the age determinations of stratigraphic boundaries recognised in this study, strontium isotope analyses were performed on 30 samples from selected parts of sections in most wells (Tables 3 and 4, Figs. 5-8 and 10-14). The samples were analysed according to procedures described by Eidvin et al. (1999).

The analyses chiefly utilised tests of calcareous foraminifera, but in a few cases, samples of mollusc shell fragments were used. The tests were taken mainly from sidewall and conventional cores, but ditch cutting samples were also used. Analyses were performed preferentially on foraminifer taxa with well-documented stratigraphic ranges, especially when analysing tests from ditch cutting samples.

In Tables 3 and 4, the ages of samples younger than 6.5 Ma are determined according to the Sr-record of both Farrell et al. (1995) and Howarth & McArthur (1997). The ages of older samples are based on the Sr-record of Howarth & McArthur (1997). If not stated otherwise, all ages reported in the text are based on Farrell et al. (1995). Our discussions in this paper are chiefly based on ages derived from the mean strontium isotope value of two or more samples.

It is important to note that the curve of Farrell et al. (1995) gives slightly younger ages than that of Howarth & McArthur (1997) in the range between 2 and 6 Ma. The results from the analyses of the Neogene parts of the wells are plotted in Fig. 14. This figure also shows a slightly modified version of the Farrell et al.'s (1995) curve. The figure demonstrates the precision of the method and the margin of error of a single data point. In the flat part of the curve (2.5-4.5 Ma), the $^{87}Sr/^{86}Sr$-ratio changes very little through time. As a result, the precision, using a standard deviation of 0.0000020, is much less (about ±1 Ma) than in the steeper part of the curve (about ±0.2Ma).

The Pleistocene succession was sampled in well 31/3-1 on the Troll field. The two ditch cutting samples taken just above the base of the section (sample number 1 and 2 in Table 4 and Fig. 5), have a Sr-isotope composition close to that of present day seawater. Taking the uncertainty of the method into account this corresponds to a maximum age of 0.5 Ma. According to Sejrup et al. (1995), the base of the Pleistocene section is dated to approximately 1.2 Ma in a cored geotechnical borehole, located nearby. The young ages in well 31/3-1 might be derived from caved material in the Sr samples.

Samples 20 and 25 (Table 3) were sidewall cores taken from the prograding Upper Pliocene succession in wells 34/7-1 and 34/4-7, respectively. Their mean value (0.709074) corresponds to an age of 1.9 Ma according to Farrell et al. (1995) and 2.1 Ma according to Howard & McArthur (1997). These ages agree with those suggested by biostratigraphic data.

Most of our samples have been taken from the basal Upper Pliocene unit. Samples from the core in well 34/8A-1H were analysed in two different laboratories. The strontium isotope values measured at laboratory A (Table 3, Fig. 8) were systematically higher than those obtained from laboratory B (Table 4, Fig. 8). The mean values of seven samples (11-17) analysed at laboratory A (0.709026), and of the same samples analysed at laboratory B (0.709061), give ages of 4.5 and 2.3 Ma, respectively. This suggests both Early and Late Pliocene ages for the core samples in this unit. Four sidewall cores analysed at laboratory A, also from the basal Upper Pliocene unit (samples 21, 26-28, Table 3), give a mean value of 0.709050 and a corresponding age of 3.0 Ma. Four core samples from the base of this unit in well 34/8-9S were analysed at laboratory B only (samples 7-10 in Table 4 and Fig. 7). The results obtained from these samples varied significantly, yielding ages from 1.9 to 5.6 Ma.

The upper glauconitic unit of the Utsira Formation sands has been sampled in five of the Tampen wells. The Sr-isotopic results are very similar for all samples, with the exception of sample 30 in well 34/2-4 which is probably erroneous. The values from samples 4, 18, 22 and 23 (Table 3) correspond to ages of 4.6, 5.1, 4.7 and 5.0 Ma, respectively, according to

Farrell et al. (1995). Following Howarth & McArthur (1997), the corresponding ages are 5.0, 5.6, 5.1 and 5.4 Ma. These samples are taken from a period when the isotopic composition of seawater changed rapidly. The data suggest that the glauconitic unit was deposited close to the Miocene/Pliocene boundary (5.23 Ma), which agrees with the age estimated from biostratigrapic data.

The Oligocene was sampled from ditch cuttings in four of the Tampen wells. All samples were taken from the upper part of the unit (samples 5, 6, 19, 24, 29, Table 3). The Sr values range from 0.708026 to 0.708120, and correspond to ages of about 26-28 Ma. The values are similar to those obtained from the Branden Clay and the lower part of the Vejle Fjord Formation in Denmark (Y. Rundberg, unpublished data). These results indicate that deposits from a large interval in the Upper Oligocene is absent in the Tampen area.

The lower part of the Oligocene succession was analysed in well 31/3-1 on the Troll field. One sample from this unit, taken just below the base Pleistocene unconformity, gives an age of 32.8 Ma (sample 3 in Table 4 and Fig. 1). This agrees with the age reported by Rundberg & Smalley (1989) from the same well, and also with that reported by Sejrup et al. (1995) for the same unit.

In summary, strontium isotope stratigraphy has been useful for dating all analysed units, with the exception of the basal Upper Pliocene section. Values from this interval varied considerably and gave no conclusive age determination. There could be several other reasons for inconsistent strontium ages in addition to precision problems in the interval 2.5-4.5 Ma. These may include analytical errors, reworking or caved fossil tests, impurities within the tests and other factors. Although many of the values obtained in this unit correspond to an Early Pliocene age, we suggest a Late Pliocene age required that the biostratigraphic data and the age correlation of these are correct. This age is also in agreement with sequence stratigraphic interpretation, inasmuch as that the unit consists of gravity flow deposits which we interpret to be genetically linked to the Upper Pliocene prograding system.

Palaeoenvironments

The determination of bathymetric environments used in this study is according to van Hinte (1978), who defines the following; inner neritic: 0-30 m, middle neritic: 30-100 m, outer neritic: 100-200 m and upper bathyal: 200-600 m.

Lower Oligocene

The Lower Oligocene N-G assemblage is only recorded in well 31/3-1 from the Troll Field (Figs. 15-17). The assemblage contains a medium to high diversity calcareous benthic foraminiferal fauna. Radiolarians and pyritised diatoms are also quite common. A few agglutinated benthic foraminifera are recorded, but no planktonic foraminifera. With the exception of *P. bulloides*, all of the recorded foraminifera are extinct species. According to Skarbø & Verdenius (1986) were *S. longiscata, S. adolphina* and *S. hirsuta* shallow water dwelling forms. *T. alsatica* and *G. soldanii mamillata* are described as shallow to deep water forms (Skarbø & Verdenius 1986, Gradstein & Bäckström 1996), and *C. contraria, K. siphonella* and *P. bulloides* as deep water forms (Skarbø & Verdenius 1986). The absence of planktonic foraminifera suggests a restricted connection with the open ocean, or the fact that thin walled tests of planktonic foraminifera are more prone to dissolution. The N-G assemblage indicates an outer neritic to upper bathyal depositional environment.

Lower to Upper Oligocene

Lower-Upper Oligocene deposits are recorded in wells 34/8-1 (assemblage N-F1; Visund Field), 34/8-3A (assemblage N-F2; Visund Field), 34/7-1, 34/4-7, 34/4-6 (assemblage N-F1; Snorre Field) and well 34/2-4 (assemblages N-F3 and N-F4; Figs. 15 and 16). The fossil assemblages in these intervals are dominated by sponge spicules, radiolarians and pyritised diatoms. Far fewer benthic foraminifera are recorded, and these are mainly calcareous forms, although some agglutinated forms are also present. No *in situ* planktonic foraminifera are recorded. Assemblage N-F4 in well 34/2-4 contains only sponge spicules, radiolarians and pyritised diatoms. All the recorded foraminifera are extinct species with the exception of *E. umbonatus*. *G. soldanii girardana* and *T. gracilis* occur in most intervals and were deep water forms (Skarbø & Verdenius 1986). *G. soldanii mamillata* and *T. alsatica* were deep to shallow water forms (Skarbø & Verdenius 1986, Gradstein & Bäckström 1996). *C. dutemplei*, which is recorded in some of the units, was a deep to shallow water form (Skarbø & Verdenius 1986). *E. umbonatus*, which is recorded over only limited intervals, has a recent bathymeteric range extending mainly along the lower part of the continental slope (Mackensen et al. 1985, Sejrup et al. 1981), but it is suggested that this species inhabited shallower water during the Oligocene. The high concentration of radiolarians and diatoms indicates a relatively deep, open marine environment. Low oxic to hypoxic bottom conditions, indicated by the presence of agglutinated foraminifera, may have caused the dissolution of planktonic foraminiferal tests. In conclusion, the bathymetric environment was probably upper bathyal during deposition of the Lower-Upper Oligocene succession.

Lower Miocene

Lower Miocene deposits are recorded in the Visund wells 34/8-1 (assemblage N-E) and 34/8-3A (assemblages N-D and N-E; Figs. 15 and 16). Most of the fossils recorded in these units are diatoms, radiolarians and sponge spicules (both rod-shaped and *Geodia* sp.). The N-D assemblage in well 34/8-3A contains sporadic calcareous benthic foraminifera including *E. umbonatus,* which in recent sedimentary environments is a deep water form (Mackensen et al., 1985, Sejrup et al. 1981). The high concentration of radiolarians and diatoms indicates relatively deep, open marine environments. The scarcity of planktonic and benthic calcareous foraminifera indicates hypoxic bottom conditions and dissolution of most calcareous tests. The bathymetric environment was probably upper bathyal during deposition of the Lower Miocene succession.

Upper Miocene to lowermost Lower Pliocene

Upper Miocene to lowermost Lower Pliocene deposits contain the N-C1 assemblage which is recorded in wells 34/8-1, 34/8-3A (Visund Field), 34/4-7, 34/4-6 (Snorre Field) and well 34/2-4 to the north. Sediments of this age also contain the N-C2 assemblage in well 34/7-1 (Snorre Field; Figs. 15 and 16). These glauconitic sandy units contain only a fair number of microfossils. The benthic assemblages in these deposits include calcareous foraminifera and sponge spicules. A few agglutinated foraminifera are also recorded. Sponge spicules (both rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. *In situ* planktonic foraminifera are scarce. Of the *in situ* benthic foraminiferal species, about one half is extinct. According to Skarbø & Verdenius (1986) the extinct *E. variabilis, C. dutemplei* and *U. pygmea langeri* are indicaters of deep to shallow water conditions, whereas *M. communis* was a deep water form. In recent deposits, *P. bulloides, N. affine* and *C. teretis* have a bathymeteric range extending mainly along the upper part of the continental slope and outer shelf. However, *N. affine* and *C. teretis* also occur on middle and inner shelf areas in smaller numbers (Mackensen et al. 1985, Sejrup et al. 1981). The sponge spicules *Geodia* sp. are indicators of deep to shallow water environments (Skarbø & Verdenius 1986). No fossils typical of shallow marine conditions are recorded in these deposits, and most of the benthic fossils indicate deposition in the deeper part of the shelf. However, planktonic foraminifera are few in number, and these are common in the deep shelf deposits of Late Miocene age in the central North Sea (Eidvin et al. 1999) and on the Norwegian Sea continental shelf (Eidvin et al. 1998). This may be explained by the fact that planktonic foraminifera are more buoyant and more readily sorted out than most benthic foraminifera, or that the thin walled tests of planktonic foraminifera are more readily dissolved. A further explanation may be that some of the benthic forms known from recent deposits, inhabited shallower water depths during the Late Miocene. The interpretation of bathymetric conditions based only on biostratigrapic criteria during deposition of these units is therefore somewhat complex and inconclusive. However, glauconitic facies are most common on outer present-day shelves (200-300 m; Odin & Matter 1981, Van Houten & Purucker 1984), and we propose that the sedimentary environments during the latest Miocene to earliest Pliocene probably were outer neritic.

Upper Pliocene

Upper Pliocene sediments containing the N-B1 assemblage are recorded in wells 34/8-1, 34/8A-1H, 34/8-3A (Visund Field), 34/7-1, 34/4-7, 34/4-6 (Snorre Field) and 34/2-4. Sediments of this age also contain the N-B2 assemblage in well 34/8-9S (Visund Field; Figs. 15 and 16). The assemblages in these deposits are dominated by calcareous benthic foraminifera. Planktonic foraminifera are also quite common in certain intervals, but are generally less frequent than benthic species. The fauna is relatively uniform throughout these units, but this observation is partly due to extensive caving. With the exception of *C. grossus* and *E. hannai,* all the *in situ* benthic foraminifera are extant. According to Skarbø & Verdenius (1986) and King (1989), *E. hannai* inhabited shallow water, whereas *C. grossus* was a deep to shallow water form. The extant *N. affine* and *C. teretis* which are common in most intervals are most common in deeper shelf environments. *C. reniforme* which is common in certain intervals primarily inhabits upper slope and outer shelf. It is also found in smaller numbers on the middle and inner shelf (Mackensen et al. 1985, Sejrup et al. 1981). *C. lobatulus* which is common in most sections primarily inhabits the inner part of the shelf, but is also found on the middle and outer shelf (Sejrup et al. 1981). Several shallow water forms of the genus *Elphidium* including *E. groenlandicum, E. albiumbilicatum* and *E. bartletti,* occur in varying abundances in most intervals (Skarbø & Verdenius 1986). The deep to shallow water forms *E. excavatum*, *C. scaldisiensis, H. orbiculare, B. marginata, I. norcrossi* and *I. islandica,* also occur in varying numbers in most intervals (Skarbø & Verdenius 1986).

The basal Upper Pliocene unit was sampled in detail in the cored sections in wells 34/8A-1H and 34/8-9S. Analyses revealed that shallow marine foraminifera were concentrated in clasts interpreted as being included within the debris flow deposits and therefore transported into position. In the autochthonous clays and silts the observed planktonic species and benthic foraminifera are typical of the deeper parts of the shelf. The fossil fauna in most intervals within the Upper Pliocene units indicates deposition in outer neritic to upper bathyal bathymetric environments. The presence of a high concentration of ice-rafted pebbles, together with the occurrence of several polar foraminifera of the genera *Elphidium* and *Islandica* indicate cold water conditions during most of the Late Pliocene.

The well resolved clinoformal pattern of the Upper Pliocene deposits (Fig. 2) gives a direct estimate of the palaeo-waterdepths of this time. During a late stage of progradation the height of the prograding system is close to 400 m. Such large depths were probably not present at the initial phase of progradation and at the time when the basal Upper Pliocene unit was deposited. Although much of the oldest part of the system has been eroded, we suggest that the water depth was in the order of 150-200 m at the onset of progradation, and that it gradually increased to a maximum of about 400 m as the system evolved during Late Pliocene. Significant changes in water depths, however, took place at periods when the erosion surfaces were formed.

Pleistocene

Pleistocene sediments, containing the N-A assemblage, are sampled only in well 31/3-1 (Troll Field; Figs. 15-17). This assemblage is also dominated by calcareous benthic foraminifera. Planktonic foraminifera are noticeably less frequent than the benthic taxa, but even these are quite numerous in the lower part of the unit. All the taxa are extant species. According to Skarbø & Verdenius (1986) *N. labradoricum, C. reniforme, B. marginata, E. excavatum, H. orbiculare, C. teretis, A. angulosa, I. norcrossi, I. helenae, I. islandica*, and *A. fluens* inhabit deep to shallow water environments. *N. affine* and *Pyrgo bulloides* are deep water forms and *C. lobatulus* and *U. mediterranea* inhabit shallow water environments. This indicates that Pleistocene sediments were probably deposited in middle neritic environments. A higher concentration of planktonic foraminifera in the lower part of the interval may indicate somewhat greater water depth during the deposition of this unit (middle to outer neritic). A high concentration of ice-rafted pebbles and the common occurrences of polar foraminifera of the genera *Elphidium* and *Islandiella* plus *C. reniforme* indicate cold water condition. The presence of several boreal forms, such as *U. mediterranea, A. angulosa* and *B. skagerrakensis* indicates that the cold environments were separated by shorter and warmer interglacials (Feyling-Hanssen 1983).

Discussion

Utsira Formation

In the type section in the southern Viking Graben, the Utsira Formation comprises an alternating series of sands and claystones with a gross thickness in excess of 400 m. Isaksen & Tonstad (1989) suggested a shallow marine depositional environment for the Utsira Formation sands and a Middle to Late Miocene age. Rundberg & Smalley (1989) and Smalley & Rundberg (1990) reported Sr-isotopic ages in well 30/3-1 of 13.5 and 18.0 Ma for the Utsira Formation based on analyses of mollusc fragments taken from ditch cutting samples. However, Goll & Skarbø (1990) challenged these datings by disputing the use of unidentified mollusc fragments, and themselves proposed an age of 8-9 Ma for the formation in the same well. Their conclusions were based on a biostratigraphical correlation with boreholes on the Vøring Plateau. In recent work by Eidvin et al. (1999; referring to well 15/12-3) and supported by the same author's personal observation in wells 16/1-2, 16/1-4 and 24/12-1, a latest Middle Miocene to Early Pliocene age is proposed for the Utsira Formation. Preliminary results from well 35/11-1 to the east of the study area indicate a Late Miocene to possible latest Middle Miocene age (T. Eidvin, personal observation). In this well the formation occurs as a coarse-grained, quartzose sand.

In blocks 30/6 and 30/3, the Utsira Formation comprises an approximately 200 m thick stacked series of sands with minor finer-grained interbeds. The sands are dominantly quartzose, but contain also beds rich in calcareous shell debris and glauconite. Rundberg (1989) discussed the overall depositional framework of the Utsira Formation and suggested a model involving accumulation of sands in a shallow marine setting following tectonic uplift of the northernmost North Sea area. In his regional study, Gregersen (1997) favoured a turbiditic origin of the sands, whereas Martinsen et al. (1999) indicated a shallow marine origin largely in agreement with the model of Rundberg (1989).

The main Utsira Formation sands are not recorded in any of the wells examined in the present work, and we have not made detailed seismic investigations of these deposits. The overlying glauconite rich sands in the Tampen area contain no shallow marine fossils. This may give indirect support to a turbiditic origin for the underlying main Utsira Formation sands, and this is in turn indicated by their massive character and blocky gamma-ray nature.

As mentioned previously, the term "Utsira Formation" has been used imprecisely by many consultants and other scientists/geologists and has generally been applied to all sandy intervals at the base of the Neogene section in the northern North Sea. Investigations of the Tampen wells described in this paper, show that lowstand deposits and turbiditic sands that belong to the Upper Pliocene prograding complex have erroneously been included in the Utsira Formation (Fig. 2). These sediments are separated from the underlying Utsira Formation proper by a hiatus encompassing the later Early Pliocene and earliest Late Pliocene. In some areas, it is difficult to differentiate between sands of Miocene and Late Pliocene age, and it has therefore been appropriate to include all lower Neogene sands within the Utsira Formation. We propose that the term "Utsira Formation" should only be used for sands of Miocene to Early Pliocene age and not for those belonging to the Upper Pliocene prograding complex. The top of the Utsira Formation is, in this part of the basin, defined as the top of the glauconite-rich unit close to the Miocene-Pliocene transition. Further work on the lower Neogene sandy sequences, particularly in the Gullfaks/Statfjord region, will be required in order to obtain a regional lithostratigraphic overview, and to resolve the chronostratigraphy of the late Tertiary in the northern North Sea.

Utsira Formation/glauconitic unit

We interpret that the glauconite-rich sand that overlies the Oligocene deposits in the Snorre wells and the lower Miocene in the Visund wells drapes over the main Utsira Formation further east. This interpretation is illustrated in Fig. 2. This model is based on the observation of comparable glauconite-rich intervals at the top of the Utsira Formation sand in wells from blocks 30/3 and 30/6 to the south (Rundberg 1989). Gregersen (1998) reported a high gamma peak which was interpreted to represent a glauconite-rich sand bed at the top of the Utsira Formation in blocks 35/10 and 35/11 (north-west of the Troll Field; Fig. 1). The present work proposes that the glauconitic sand of the Tampen area was deposited during the latest Miocene and into the earliest Pliocene. However, there are indications that these sands may have been deposited over a longer period, and that they interfinger with the main Utsira Formation sands to the east. Firstly, the sand unit is about 15 m thick, homogeneous, and according to sidewall cores and log data, rich in glauconite minerals. This may indicate that the unit consists of a series of stacked units, each representing a condensed interval. Secondly, the recorded *Bolboforma* species observed in wells 34/8-1 and 34/8-3A, indicate an age of 12

Ma (Spiegler & Müller 1992) for this unit. This age, combined with the Sr-isotopic data from the unit, indicate a period of about 6-7 m.y. characterised by an overall low rate of sedimentation. However, *Bolboforma* are not recorded in any of the other wells in the Tampen area, indicating that they most likely are reworked. If this is the case, it is likely that the *E. variabilis* (N-C1) assemblage is younger than the *Bolboforma* zones of Spiegler & Müller (1992) and Müller & Spiegler (1993) recorded in the North Atlantic and the Norwegian Sea. The youngest of these zones (*B. metzmacheri* Zone) corresponds to an interval of between 10.0-8.7 Ma based on calibration with nannoplankton and palaeomagnetic data. This suggestion is based on the comparison of the observations from the Norwegian Sea continental shelf where the *E. variabilis* and *Bolboforma* assemblages are present in the same wells (Stratlab 1986, Eidvin et al. 1998). The young Sr-ages obtained from this unit also support this view, and indicate a period of condensed deposition of approximately 3.5 m.y. However, Gradstein & Bäckström (1996) have observed the LAD of *B. metzmacheri* stratigraphically above that of *E. variabilis* in the North Sea, which is not in concurrence with our view. The authors agree with Gradstein & Bäckström (1996) that further studies of the late Miocene are required to resolve this question.

The basal Upper Pliocene unit

In previous papers and in well reports from the Snorre and Visund areas, the basal Upper Pliocene unit has commonly been assigned a Miocene age and consequently been included in the Utsira Formation. In a study of wells 34/2-4 and 34/2-6, Eidvin & Riis (1992) reported a Late Miocene age for this unit and also included it in the Utsira Formation. Gradstein et al. (1992) assigned the unit an Early Miocene age in well 34/8-1. Steurbaut et al. (1991), assigned the lower part of the unit in well 34/4-1 to the Early Pliocene, but were unable to determine the age of the upper part. It must be emphasised that all of these datings were based on ditch cuttings, and that consequently the unit boundaries were based on the LADs of selected taxa. The present work, which has utilised cores from wells 34/8-9S and 34/8A-1H (Figs. 7 and 8), and sidewall cores from wells 34/4-7 and 34/7-1 (Figs. 11a and 12a), has demonstrated an *in situ* Upper Pliocene fauna within this unit, and has shown that the older fossils are reworked.

There is good evidence from the cores of a glacio-marine influence within the sediments from this unit. Glacio-marine sediments of the Vøring Plateau have been the subject of studies by Jansen & Sjøholm (1991) and Fronval & Jansen (1996). These studies demonstrated the presence of ice-rafted material in sediments as old as 12.6 Ma. The frequency of ice-rafted material increases during the period between 7.2 and 6.0 Ma, but remains relatively low between 6.0 Ma and 2.75 Ma. A marked increase in the supply of such material after about 2.75 Ma reflects the expansion of the northern European glaciers (Fig. 17). The maximum age of the basal Upper Pliocene unit of the Tampen area is therefore assigned to be 2.75 Ma.

Origin of the incised valley/canyon system west of Sognefjorden

The large incised valley/canyon system (Fig. 1) was first described by Rundberg et al. (1995). These workers proposed that it was formed as part of a fluvial system resulting from uplift of the northernmost North Sea during the Miocene. Martinsen et al. (1999) also favoured a Miocene age and a fluvial origin. Gregersen (1998) published a study based on the interpretation of 3-D seismic and concluded that the channel-like system was formed prior to deposition of the Utsira Formation, and further proposed a latest Oligocene or earliest Miocene age for the incision.

The present authours' seismic interpretation indicates that the timing of the valley/canyon incision is best resolved by correlating from wells in the northernmost part of the North Sea where the Neogene succession is preserved. In this area, it is evident from both 2-D and 3-D seismic data that the erosive event postdates deposition of the basal Upper Pliocene unit. This relationship is illustrated in Fig. 3. Therefore, we propose that the elongate erosive system is Late Pliocene in age. The dimension of the erosive form, from 1-4 km wide and 150-200 m deep (Figs. 1 and 3), is a magnitude larger than for normal large fluvial streams. The structure is therefore considered to have formed by valley incision more than single fluvial channeling, alternatively as a submarine canyon, or a combination.

Although glacial conditions prevailed at North Sea latitudes during Late Pliocene, a subglacial origin of the canyon is not considered likely. Expansion of ice sheets out onto the shelf probably first took place at about 1.2 Ma (Jansen & Sjøholm 1991, Sejrup et al. 1995). The climatic deterioration at this time is also shown in the oxygen isotope record (Mix et al. 1995).

At this time, the northern North Sea area is interpreted to have been a shelf platform with slope and deeper basin settings developed in the present day Møre Basin to the north. The incised valley system thus cuts deeply into the entire palaeoshelf. This would require a large fall in relative sea level, as indicated from seismic data. This fall in relative sea level resulted in subaerial exposure of marginal parts of the northern North Sea basin. The fluvial incision of the emerged shelf was accompanied by uplift and erosion of the Fennoscandian landmass, followed by large-scale progradation and rapid subsidence of the palaeoshelf. The progradational Upper Pliocene shelf sediments demonstrate that the fall in relative sea level was succeeded by a rapid rise in relative sea level, creating the accommodation needed for this regressive unit.

We propose that, at the time of valley/canyon incision, the shelf edge probably exhibited an east-west orientation close to 62°N. Subaerial exposure has affected much of the eastern part of the basin, such as the areas between 61°15'N and the Agat area at 62°N, where another deep erosive system is observed (Rundberg & Eidvin 1999). This latter system cuts into shelf sediments which are eroded to the south, and is most likely fluvial in origin. The west of Sognefjorden valley incision is closely contemporaneous with the Agat incision, but the shelf exposure was probably more extensive in the west of Sognefjorden area.

The present authors therefore favour a model whereby fluvial drainage prevailed over much of quadrant 35. However, in block 34/3 we propose a continuation of the incised valley as a submarine canyon migrating towards the north and cutting into the outer palaeoshelf. This submarine canyon may have supplied sediment to a slope canyon or a turbidite channel system at the southern margin of the Møre Basin. It is also possible that large-scale slumping on the palaeoslope of the Møre Basin may have introduced retrogressive failure and the development of elongate shelf canyons or channels similar to those described in models presented by Talling (1998) and Eyles & Lagoe (1998).

The question if the incision was controlled by glacial eustacy or tectonics remains to be aired. According to data presented by Shackleton et al. (1995), a eustatic sea-level fall in the order of 50-60 m was associated with glacial stage G6 at about 2.75 Ma. Our seismic interpretation and palaeogeographic reconstruction suggest that a larger relative sea-level fall than this must have taken place in the northern North Sea at the time of incision. It is important to note that our model also requires a succeeding rapid rise in sea level to create the accommodation space needed for the regressive Upper Pliocene unit. We therefore propose that tectonic mechanisms exerted major control of sea-level changes that led to exposure and incision of the eastern marginal parts of the northern North Sea basin.

Summary and conclusion

In summary, we conclude the following:

1) In the Troll area Pleistocene deposits rest unconformably on Lower Oligocene strata. The upper part of the Upper Oligocene is absent in all the Tampen wells studied. In the Visund area (block 34/8) there is a hiatus of more than 2 m.y. between Oligocene and Lower Miocene deposits. In the Snorre area (blocks 34/4 and 34/7) there is a hiatus of more than 18 m.y. between the Oligocene and the Upper Miocene (Fig. 16).

2) A previously undescribed Lower Miocene unit has been identified and mapped at the top of the Hordaland Group in the Visund area. A large hiatus separates this unit from the overlying beds.

3) The quartzose sands of the Utsira Formation are not recorded in any of the studied wells, but preliminary results from well 35/11-1 indicate a Late Miocene to possible latest Middle Miocene age for the formation. A glauconitic part of the Utsira Formation (Late Miocene to earliest Early Pliocene in age) is present in the Tampen wells. This unit overlies the Oligocene strata in the Snorre area and the Lower Miocene strata in the Visund area. East of these areas, we propose that the unit drapes over, or partly interfingers with the main Utsira Formation sands.

4) A distinct seismic unit is identified at the base of the Upper Pliocene prograding complex. Cores from this unit contain sands and silts interpreted to be gravity flow deposits, and contain mudstone clasts that include shallow marine faunas interpreted to have been transported into deeper water. Ice-rafted debris are also common in the cores. The fauna is typical of the Late Pliocene, but reworked Miocene forms are also quite common.

5) We believe that the Utsira Formation requires a new and precise definition as a basis for further stratigraphic study in the northern North Sea. The present authors propose that the top of the formation should be assigned to end of the period of restricted sedimentation, characterised by glauconite rich sands. This point in time is close to the Miocene-Pliocene boundary, as we have demonstrated in the Tampen wells. Thus, we recommend that sands belonging to the basal Upper Pliocene unit or to the Upper Pliocene prograding complex should not be included in the Utsira Formation. There is also a need for a clearer definition of the base of the Utsira Formation because there remains considerable confusion, in some areas further to the south, whether the sands belong to the Skade or to the Utsira Formations.

6) The elongate erosive channel-like structure west of Sognefjorden, which has been described as Miocene in age, appears to be younger. The structure is inferred to have formed

as an incised valley in the proximal areas and as a submarine canyon in its extension further to the north into the Møre Basin. The valley/canyon incision postdates deposition of the basal Upper Pliocene unit in the Tampen area, which was deposited in a lowstand setting. We propose that the erosive drainage system evolved during Late Pliocene time, initiated by a large fall in relative sea level. This was succeeded by a rise in relative sea level giving accommodation for the progradation of the Upper Pliocene shelf wedge.

Acknowledgement

The authors extend their thanks to Finn Moe, Bjørg Ruus, Sigrun Torrissen and Inger M. Våge for careful and accurate technical assistance and to Rune Goa and Per Torgersen for preparation of the illustrations. Ane Birgitte Nødtvedt, Rolf Birger Pedersen and Helge Stray have carried out strontium isotope analyses. The authors acknowledge the benefit of discussions with Sven A. Bäckström, Sverre Ola Johnsen, Christian Magnus, Jenö Nagy, Fridtjof Riis and Robert Williams. We are grateful to Felix Gradstein and Johan Petter Nystuen whose comments improved the manuscript and to Paul Grogan who improved the English language. Tom Bugge, Karen Luise Knudsen and Morten Smelror reviewed the manuscript and offered important suggestions. We want to express our sincere thanks to these workers. We also want to thank the Norwegian Petroleum Directorate and Saga Petroleum ASA for funding the study and allowing us to publish the results.

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Tables

Table 1. Samples analysed in wells 31/3-1, 34/8-1, 34/8-9S, 34/8A-1H and 34/8-3A. DC = ditch cutting sample.

Table 2. Samples analysed in wells 34/4-6, 34/4-7, 34/7-1 and 34/2-4. SWC = sidewall cores, DC = ditch cutting sample.

Table 3. Strontium isotope ratios of Cainozoic samples analysed in laboratory A.

Table 4. Strontium isotope ratios of Cainozoic samples analysed in laboratory B.

Figures

Fig. 1. Map showing the following key elements of this work: location of studied wells of the Snorre Field area (blocks 34/4, 34/7), Visund Field area (block 34/8), northern Tampen Spur (34/2-4) and Troll Field area (block 31/3); lateral distribution of the main Utsira Formation sand (full line) and approximate outline of the Lower Miocene unit (broken line); location of seismic lines shown in Figs. 2 and 3; outline of the Upper Pliocene incised valley/canyon system and truncation line of top Oligocene surface. Studied wells are marked with black fill. F. = Field.

Fig. 2. (A) Seismic line NVGTI-92-105 across the Norwegian northern North Sea through wells 34/8-3A (Visund area) and 34/8-1 (Snorre area) illustrating the basin architecture and major depositional sequences of the upper Cainozoic. (B) Interpreted version of line NVGTI-92-105 showing major depositional sequences. The glauconitic sand unit is considered to overlie or partly interdigitate with the main Utsira Formation sand to the east. Note that the Upper Pliocene sand penetrated in well 34/7-1 is not a part of the Utsira Formation. Location of the line is shown in Fig. 1.

Fig. 3. Seismic composite line (NVGT-88-11 and MS97M inline 3794) showing the stratigraphy in well 34/2-4 and a deep canyon, incised into Oligocene strata. The line illustrates that the incision postdates deposition of the basal Upper Pliocene sequence. Location of the line is shown in Fig. 1.

Fig. 4. Log correlation diagram of wells from the Visund area (block 34/8), wells from the Snorre area (blocks 34/4 and 34/7) and well 34/2-4 on the northern Tampen Spur. Note position of conventional cores in wells 34/8-9S and 34/8-A-1H. GR = gamma ray log. Depth in metres below rig floor (RKB).

Fig. 5. Range chart of the most important index fossils in the investigated interval of well 31/3-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, SR. ANALYSES = strontium isotope analyses.

Fig. 6. Range chart of the most important index fossils in the investigated interval of well 34/8-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, μs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 7. Range chart of the most important index fossils in the investigated interval of well 34/8-9S. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. C = core, m RKB = metres below rig floor, m MSL = metres below mean sea level, SR. ANALYSES = strontium isotope analyses.

Fig. 8. Range chart of the most important index fossils in the investigated interval of well 34/8A-1H. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. C = core, m RKB = metres below rig floor, m MSL = metres below mean sea level, SR. ANALYSES = strontium isotope analyses.

Fig. 9. Range chart of the most important index fossils in the investigated interval of well 34/8-3A. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC =

ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot.

Fig. 10. Range chart of the most important index fossils in the investigated interval of well 34/4-6. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 11a. Range chart of the recorded fossils in the sidewall core samples in the investigated interval of well 34/4-7. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. SWC = sidewall core samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 11b. Range chart of the most important index fossils in the ditch cutting samples in the investigated interval of well 34/4-7. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 12a. Range chart of the recorded fossils in the sidewall core samples in the investigated interval of well 34/7-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. SWC = sidewall core samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 12b. Range chart of the most important index fossils in the ditch cutting samples in the investigated interval of well 34/7-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 13. Range chart of the most important index fossils in the investigated interval of well 34/8-1. Legend for columns: rare 0-5 %, common 5-20 %, abundant 20 % or more. DC = ditch cutting samples, m RKB = metres below rig floor, m MSL = metres below mean sea level, gAPI = American Petroleum Institute gamma ray units, µs/f = microseconds per foot, SR. ANALYSES = strontium isotope analyses.

Fig. 14. Curve showing strontium isotope evolution of seawater from 6.5 Ma to recent (modified after Farrell et al. 1995). Outer envelope represents confidence interval ($\pm 19\text{x}10^{-6}$). Ages have been derived by plotting the Sr-isotope results to the mean polynomial curve. Only Sr-isotope results from laboratory A are shown. All values are plotted relative to SRM-987 = 0.710235.

Fig. 15. Correlation of fossil assemblages between the wells studied. Vertical axis is metres below rig floor.

Fig. 16. Correlation of the fossil assemblages between the well studied. Vertical axis is in Ma. FA = fossil assemblages.

Fig. 17. Correlation of faunal assemblages between well 31/3-1, 34/8-1 and 34/4-6 as well as from the wells to King's (1989) North Sea fossil zonation and to the fossil zonation of the ODP sites 642 and 643 on the Vøring Plateau (Spiegler & Jansen 1989, Müller & Spiegler 1993). The shaded part of the wells is not sampled. The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). S = series/subseries, L = lithostratigraphic units, FA = fossil assemblages.

SAMPLES ANALYSED IN WELL 31/3-1

- 430.0 m DC
- 440.0 m DC
- 450.0 m DC
- 460.0 m DC
- 470.0 m DC
- 480.0 m DC
- 490.0 m DC
- 500.0 m DC
- 510.0 m DC
- 520.0 m DC
- 530.0 m DC
- 540.0 m DC
- 550.0 m DC
- 560.0 m DC
- 580.0 m DC

SAMPLES ANALYSED IN WELL 34/8-1

- 440.0 m DC
- 460.0 m DC
- 480.0 m DC
- 490.0 m DC
- 500.0 m DC
- 510.0 m DC
- 520.0 m DC
- 530.0 m DC
- 550.0 m DC
- 560.0 m DC
- 580.0 m DC
- 600.0 m DC
- 630.0 m DC
- 650.0 m DC
- 680.0 m DC
- 700.0 m DC
- 730.0 m DC
- 750.0 m DC
- 780.0 m Dc
- 800.0 m DC
- 830.0 m DC
- 850.0 m DC
- 880.0 m DC
- 900.0 m DC
- 920.0 m DC
- 950.0 m DC
- 980.0 m DC
- 1000.0 m DC
- 1020.0 m DC
- 1030.0 m DC
- 1050.0 m DC
- 1060.0 m DC
- 1070.0 m DC
- 1080.0 m DC
- 1090.0 m DC
- 1100.0 m DC
- 1110.0 m DC
- 1120.0 m DC
- 1130.0 m DC
- 1140.0 m DC
- 1150.0 m DC
- 1160.0 m DC
- 1170.0 m DC
- 1180.0 m DC
- 1190.0 m DC
- 1200.0 m DC
- 1220.0 m DC
- 1240.0 m DC
- 1260.0 m DC
- 1280.0 m DC
- 1300.0 m DC
- 1320.0 m DC
- 1340.0 m DC
- 1360.0 m DC

SAMPLES ANALYSED IN WELL 34/8-9S

- 1109.68 m Core
- 1110. 52 m Core
- 1111.74 m Core
- 1112.63 m Core

SAMPLES ANALYSED IN WELL 34/8A-1H

- 1070.2 m Core
- 1083.2 m Core
- 1084.1 m Core
- 1086.1 m Core
- 1088.2 m Core
- 1101.3 m Core
- 1102.0 m Core

SAMPLES ANALYSED IN WELL 34/8-3A

- 1000.0 m DC
- 1010.0 m DC
- 1020.0 m DC
- 1030.0 m DC
- 1040.0 m DC
- 1050.0 m DC
- 1060.0 m DC
- 1070.0 m DC
- 1080.0 m DC
- 1090.0 m DC
- 1100.0 m DC
- 1110.0 m DC
- 1120.0 m DC
- 1130.0 m DC
- 1140.0 m DC
- 1150.0 m DC
- 1160.0 m DC
- 1170.0 m DC
- 1180.0 m DC
- 1190.0 m DC
- 1200.0 m DC
- 1210.0 m DC
- 1220.0 m DC
- 1230.0 m DC
- 1240.0 m DC
- 1260.0 m DC
- 1270.0 m DC
- 1280.0 m DC
- 1290.0 m DC
- 1300.0 m DC

Table 1

SAMPLES ANALYSED IN WELL 34/4-6

540.0 m DC
550.0 m DC
560.0 m DC
570.0 m DC
600.0 m DC
620.0 m DC
650.0 m DC
670.0 m DC
700.0 m DC
720.0 m DC
750.0 m DC
770.0 m DC
800.0 m DC
820.0 m DC
850.0 m DC
870.0 m DC
900.0 m DC
920.0 m DC
950.0 m DC
970.0 m DC
1000.0 m DC
1020.0 m DC
1050.0 m DC
1070.0 m DC
1100.0 m DC
1110.0 m DC
1120.0 m DC
1130.0 m DC
1140.0 m DC
1150.0 m DC
1170.0 m DC
1180.0 m DC
1190.0 m DC
1200.0 m DC
1210.0 m DC
1220.0 m DC
1230.0 m DC
1240.0 m DC
1250.0 m DC
1270.0 m DC
1290.0 m DC
1310.0 m DC
1330.0 m DC
1350.0 m DC
1370.0 m DC

SAMPLES ANALYSED IN WELL 34/4-7

1000.0 m DC
1010.0 m DC
1010.0 m SWC
1020.0 m DC
1030.0 m DC
1038.0 m SWC
1040.0 m DC
1050.0 m DC
1057.0 m SWC
1060.0 m DC
1061.0 m SWC
1063.0 m SWC
1070.0 m DC
1076.0 m SWC
1080.0 m DC
1090.0 m DC
1100.0 m DC
1104.0 m SWC
1100.0 m DC
1120.0 m DC
1130.0 m DC
1134.0 m SWC
1140.0 m DC
1150.0 m DC
1160.0 m DC
1168.0 m SWC
1170.0 DC
1180.0 m DC
1190.0 m DC
1190.0 m SWC
1192.0 m SWC
1200.0 m DC
1204.0 m SWC
1210.0 m DC
1220.0 m DC

SAMPLES ANALYSED IN WELL 34/7-1

1000.0 m DC
1010.0 m DC
1020.0 m DC
1020.5 m SWC
1030.0 m DC
1040.0 m DC
1041.5 m SWC
1050.0 m DC
1052.0 m SWC
1060.0 m DC
1062.6 m SWC
1070.0 m DC
1973.0 m SWC
1080.0 m DC
1083.5 m SWC
1090.0 m DC
1094.0 m SWC
1100.0 m DC
1102.5 m SWC
1110.0 m DC
1114.4 m SWC
1120.0 m DC
1123.0 m SWC
1130.0 m DC
1130.0 m SWC
1140.0 m DC
1143.0 m SWC
1150.0 m DC
1155.0 m SWC
1160.0 m DC
1166.0 m SWC
1170.0 m DC
1180.0 m DC
1190.0 m DC
1200.0 m DC

SAMPLES ANALYSED IN WELL 34/2-4

1300.0 m DC
1310.0 m DC
1320.0 m DC
1330.0 m DC
1340.0 m DC
1350.0 m DC
1360.0 m DC
1370.0 m DC
1390.0 m DC
1400.0 m DC
1410.0 m DC
1420.0 m DC
1430.0 m DC
1440.0 m DC
1450.0 m DC
1460.0 m DC
1470.0 m DC
1480.0 m DC
1490.0 m DC
1500.0 m DC
1510.0 m DC
1520.0 m DC
1530.0 m DC
1540.0 m DC
1550.0 m DC
1560.0 m DC
1570.0 m DC
1580.0 m DC
1590.0 m DC
1600.0 m DC

Sample no. (1)	Well	Depth (m)	Sequence	^{87}Sr/^{86}Sr Lab A (2)	S.E. (3)	Age (4) (Ma)	Age (5) (Ma)	Remarks (6)
4	34/8-1	1110-1130	Glauc. sand	0.709023	17	4.6	5.0	DC
5	34/8-1	1280	Oligocene	0.708026	45	-	28.3	DC, 4 bl.
6	34/8-1	1300	Oligocene	0.708042	47	-	27.8	DC, 1 bl.
11	34/8A-1H	1070.2	B. U. Plioc.	0.708999	29	5.1	5.6	Core, 4 bl.
12	34/8A-1H	1083.2	B. U. Plioc.	0.709018	12	4.7	5.2	Core
13	34/8A-1H	1084.1	B. U. Plioc.	0.709029	16	4.4	4.9	Core
14	34/8A-1H	1086.1	B. U. Plioc.	0.709011	13	4.8	5.3	Core
15	34/8A-1H	1088.2	B. U. Plioc.	0.709026	14	4.5	5.0	Core
16	34/8A-1H	1101.3	B. U. Plioc.	0.709038	18	4.0	4.5	Core, 8 bl.
17	34/8A-1H	1102.0	B. U. Plioc.	0.709062	13	2.3	2.4	Core
18	34/4-6	1220-1240	Glauc. sand	0.708997	14	5.1	5.6	DC
19	34/4-6	1250-1280	Oligocene	0.708114	17	-	26.2	DC
20	34/4-7	1063	Progr. Plioc.	0.709068	15	2.0	2.2	SWC
21	34/4-7	1168	B. U. Plioc	0.709046	13	3.5	3.7	SWC
22	34/4-7	1192	Glauc. sand	0.709019	13	4.7	5.1	SWC
23	34/4-7	1180-1200	Glauc. sand	0.709007	13	5.0	5.4	DC
24	34/4-7	1210	Oligocene	0.708064	39	-	27.4	DC, 5 bl.
25	34/7-1	1062.5	Progr. Plioc.	0.709080	14	1.7	1.9	SWC
26	34/7-1	1094	B. U. Plioc.	0.709075	15	1.8	2.0	SWC
26A	34/7-1	1102.5	B. U. Plioc.	0.709022	15	4.6	5.1	SWC, 3 bl.
27	34/7-1	1123	B. U. Plioc.	0.709034	20	4.2	4.7	SWC
28	34/7-1	1130	B. U. Plioc.	0.709073	29	1.8	2.1	SWC, 8 bl.
29	34/7-1	1190-1200	Oligocene	0.708120	29	-	26.1	DC, 4 bl.
30	34/2-4	1470-1490	Glauc. Sand	0.709055	11	2.5	2.6	DC

(1) Sample numbers refer to Figs. 5–13

(2) All results are normalised to SRM-987 = 0.710235 and to ^{86}Sr/^{88}Sr = 0.1194

(3) S.E. = standard error of the mean (two-sigma x 10^{-6})

(4) Age according to Farrell et al. (1995), (0-6 m.y. interval only)

(5) Age according to Howarth and McArthur (1997). Note that all results have been normalised to 0.710248 when using the Look-up Table

(6) DC = ditch cuttings; SWC = sidewall core; bl = blocks (denotes small sample, age based on x/10 blocks; 1 bl = 10 individual measurements)

Table 3

Sample no. (1)	Well	Depth (m)	Sequence	^{87}Sr/^{86}Sr Lab A (2)	S.E. (3)	Age (4) (Ma)	Age (5) (Ma)	Remarks (6)
1	31/3-1	520	Pleistocene	0.709177	12	0	0	DC
2	31/3-1	530	Pleistocene	0.709174	12	0	0.2	DC
3	31/3-1	570 - 580	Oligocene	0.707863	12	-	32.8	DC
7	34/8-9S	1109.68	B. U. Plioc.	0.709086	11	1.9	2.1	Core
8	34/8-9S	1110.52	B. U. Plioc.	0.709013	13	5.1	5.3	Core
9	34/8-9S	1111.74	B. U. Plioc.	0.709007	13	5.2	5.6	Core
10	34/8-9S	1112.63	B. U. Plioc.	0.709054	12	3.9	4.3	Core
10A	34/8-9S	1112.63	B. U. Plioc.	0.708978	10	5.6	6.2	Core
11	34/8A-1H	1070.2	B. U. Plioc.	0.709078	9	2.2	2.3	Core
12	34/8A-1H	1083.2	B. U. Plioc.	0.709080	9	2.2	2.2	Core
13	34/8A-1H	1084.1	B. U. Plioc.	0.709057	9	3.9	3.9	Core
14	34/8A-1H	1086.1	B. U. Plioc.	0.709050	9	4.2	4.5	Core
15	34/8A-1H	1088.2	B. U. Plioc.	0.709073	9	2.3	2.4	Core
16	34/8A-1H	1101.3	B. U. Plioc.	0.709097	10	1.7	2.1	Core

All explanations as in Table 3

Table 4

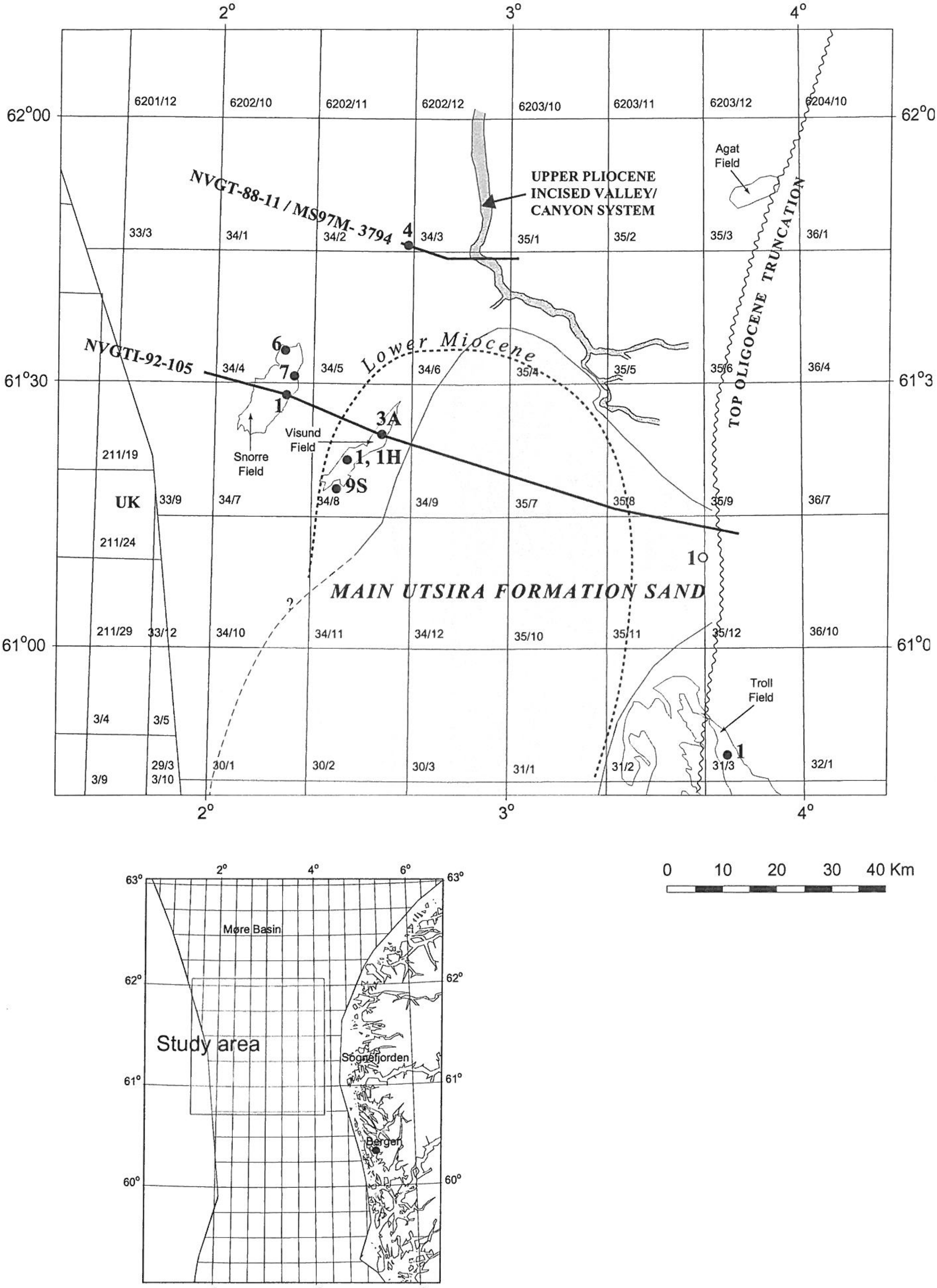

2°
3°
4°
62°00
62°0
61°30
61°3
61°00
61°0
6201/12
6202/10
6202/11
6202/12
6203/10
6203/11
6203/12
6204/10
UPPER PLIOCENE
INCISED VALLEY/
CANYON SYSTEM
Agat
Field
NVGT-88-11 / MS97M- 3794
4
33/3
34/1
34/2
34/3
35/1
35/2
35/3
36/1
TOP OLIGOCENE TRUNCATION
NVGTI-92-105
6
7
1
34/4
34/5
Lower Miocene
34/6
35/4
35/5
35/6
36/4
3A
Visund
Field
1, 1H
9S
Snorre
Field
211/19
UK
33/9
34/7
34/8
34/9
35/7
35/8
35/9
36/7
211/24
1
MAIN UTSIRA FORMATION SAND
?
211/29
33/12
34/10
34/11
34/12
35/10
35/11
35/12
36/10
Troll
Field
3/4
3/5
1
3/9
29/3
3/10
30/1
30/2
30/3
31/1
31/2
31/3
32/1
0
10
20
30
40 Km
63°
2°
4°
6°
Møre Basin
62°
Study area
Sognefjorden
61°
Bergen
60°

Figure 1

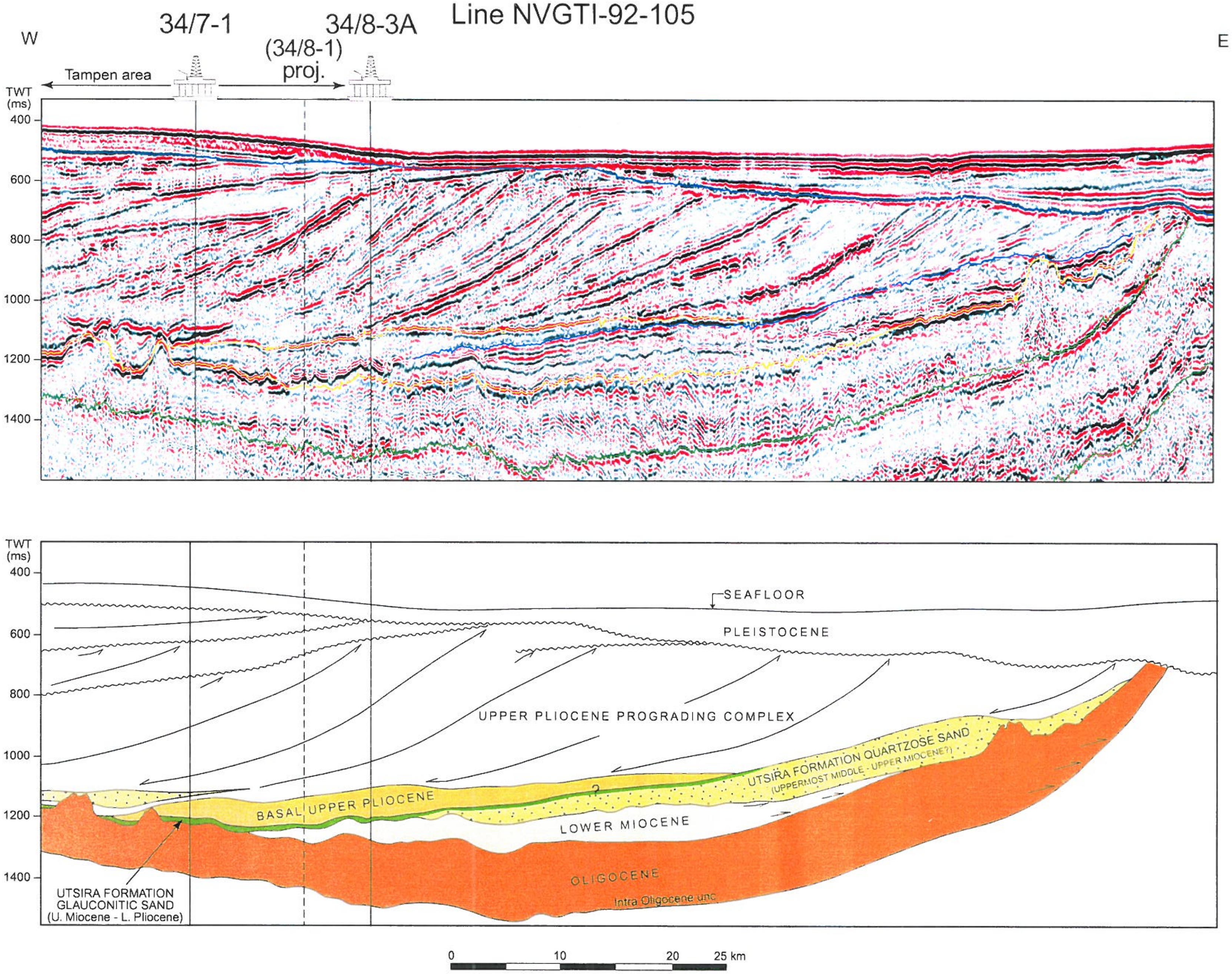

Line NVGTI-92-105
W
E
34/7-1
(34/8-1)
proj.
34/8-3A
Tampen area
TWT
(ms)
400
600
800
1000
1200
1400
SEAFLOOR
PLEISTOCENE
UPPER PLIOCENE PROGRADING COMPLEX
UTSIRA FORMATION QUARTZOSE SAND
(UPPERMOST MIDDLE - UPPER MIOCENE?)
?
BASAL UPPER PLIOCENE
LOWER MIOCENE
OLIGOCENE
Intra Oligocene unc
UTSIRA FORMATION
GLAUCONITIC SAND
(U. Miocene - L. Pliocene)
0
10
20
25 km

Figure 2

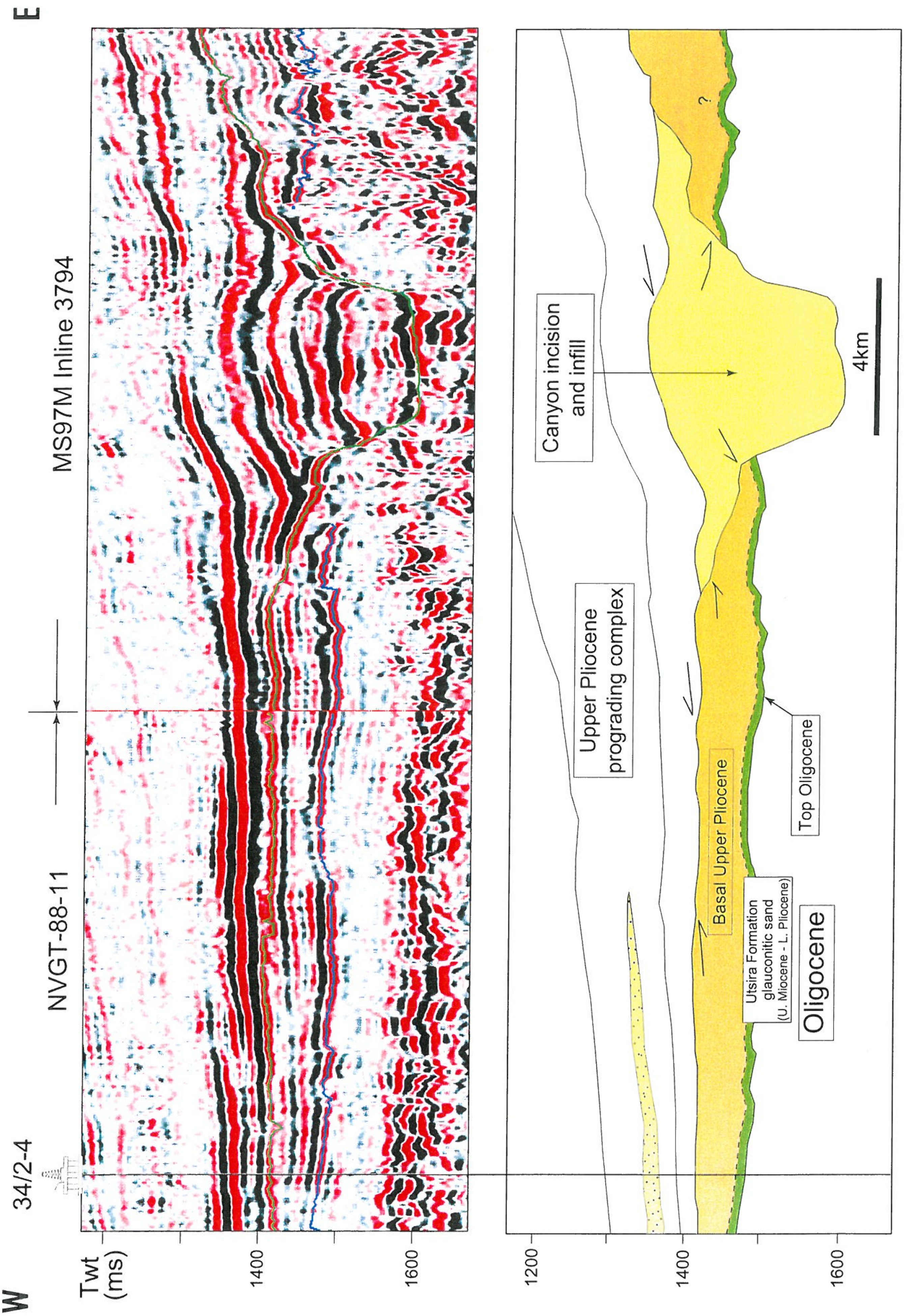

W
E
Twt (ms)
1400
1600
1200
1400
1600
34/2-4
NVGT-88-11
MS97M Inline 3794
Upper Pliocene prograding complex
Canyon incision and infill
?
4km
Basal Upper Pliocene
Top Oligocene
Utsira Formation glauconitic sand (U. Miocene - L. Pliocene)
Oligocene

Figure 3

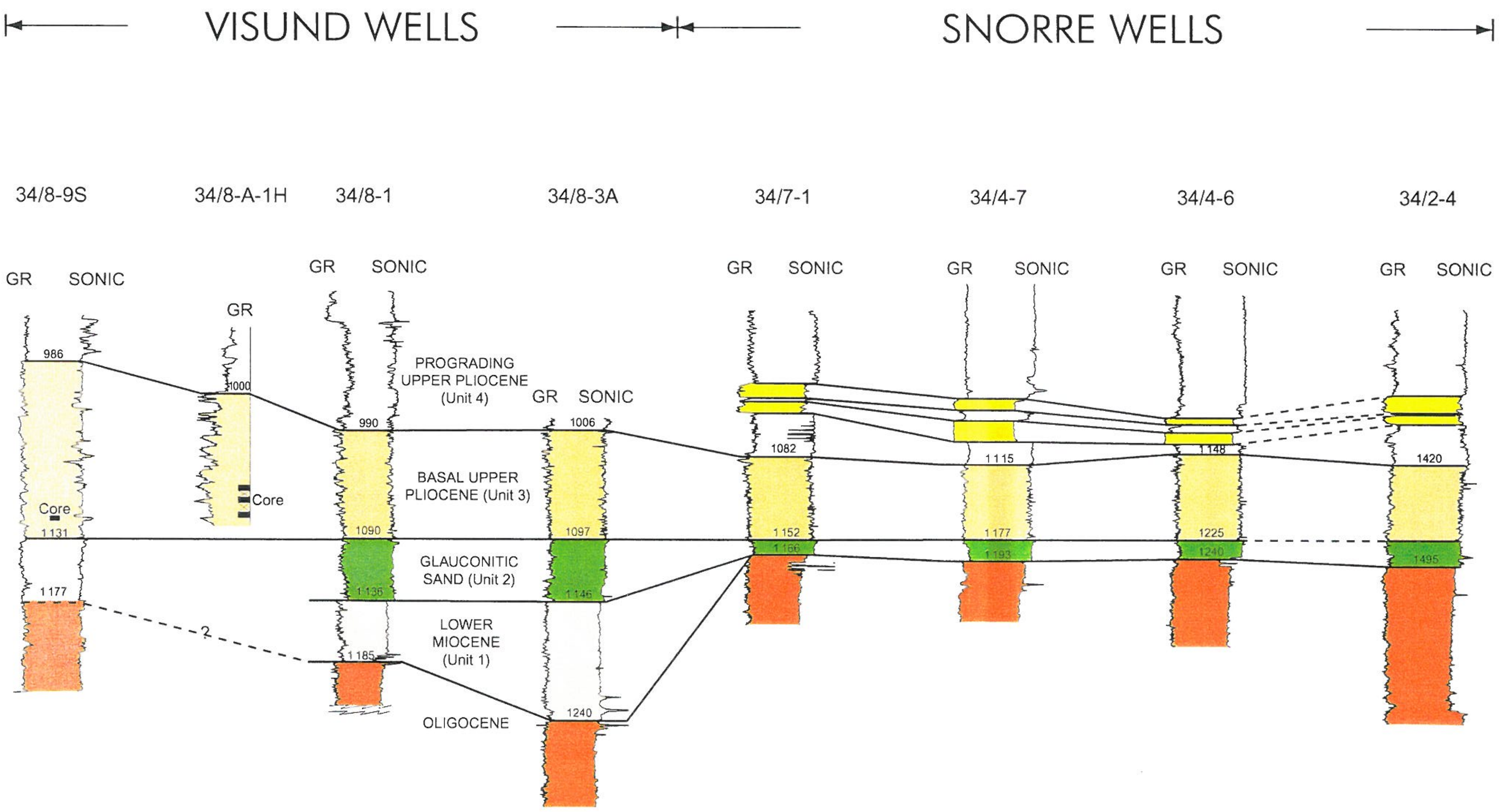

VISUND WELLS
SNORRE WELLS
34/8-9S
34/8-A-1H
34/8-1
34/8-3A
34/7-1
34/4-7
34/4-6
34/2-4
GR
SONIC
986
1000
990
1006
1082
1115
1148
1420
Core
1131
1090
1097
1152
1166
1177
1193
1225
1240
1495
1136
1146
1177
1185
1240
?
PROGRADING UPPER PLIOCENE (Unit 4)
BASAL UPPER PLIOCENE (Unit 3)
GLAUCONITIC SAND (Unit 2)
LOWER MIOCENE (Unit 1)
OLIGOCENE

Figure 4

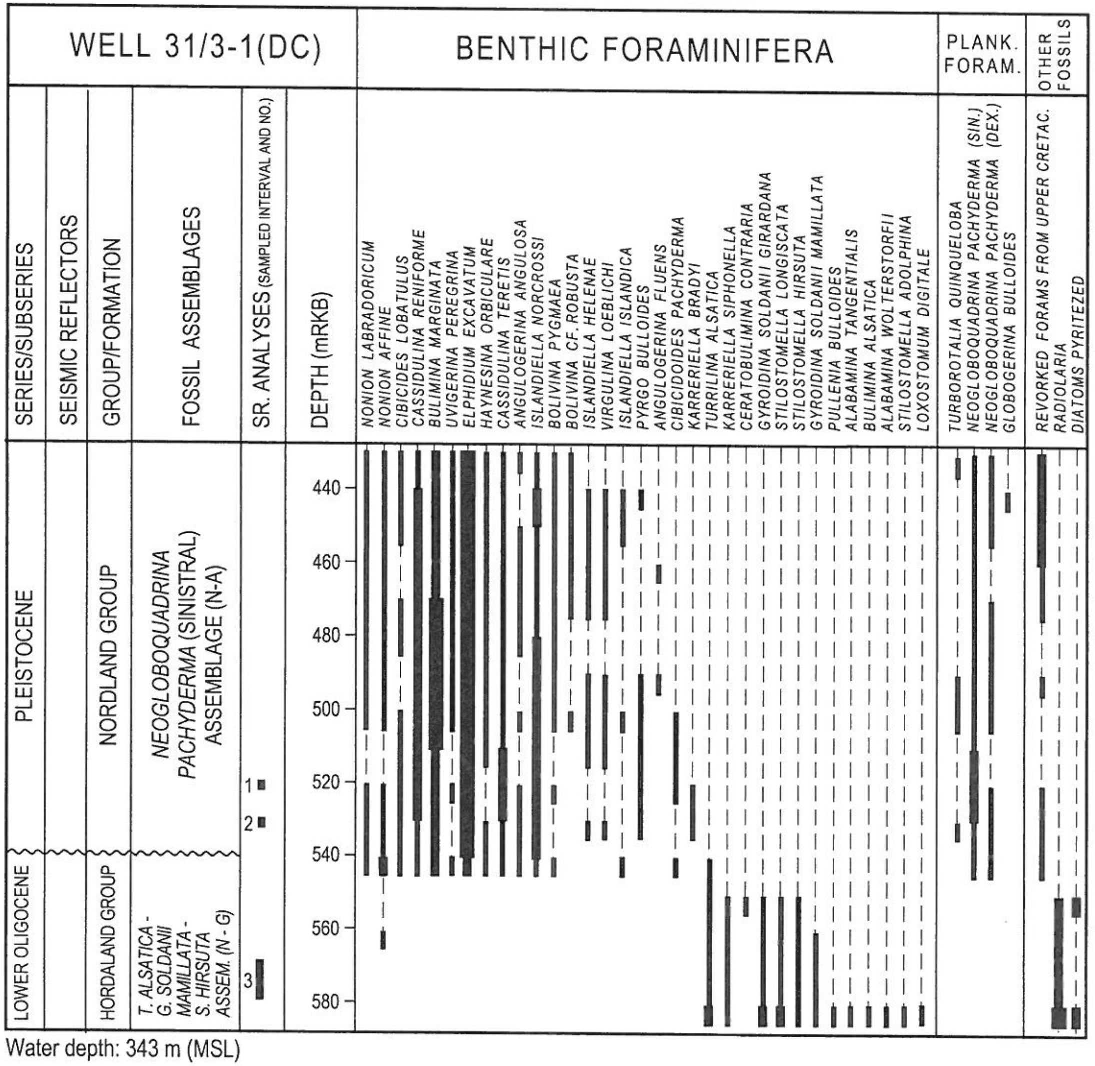
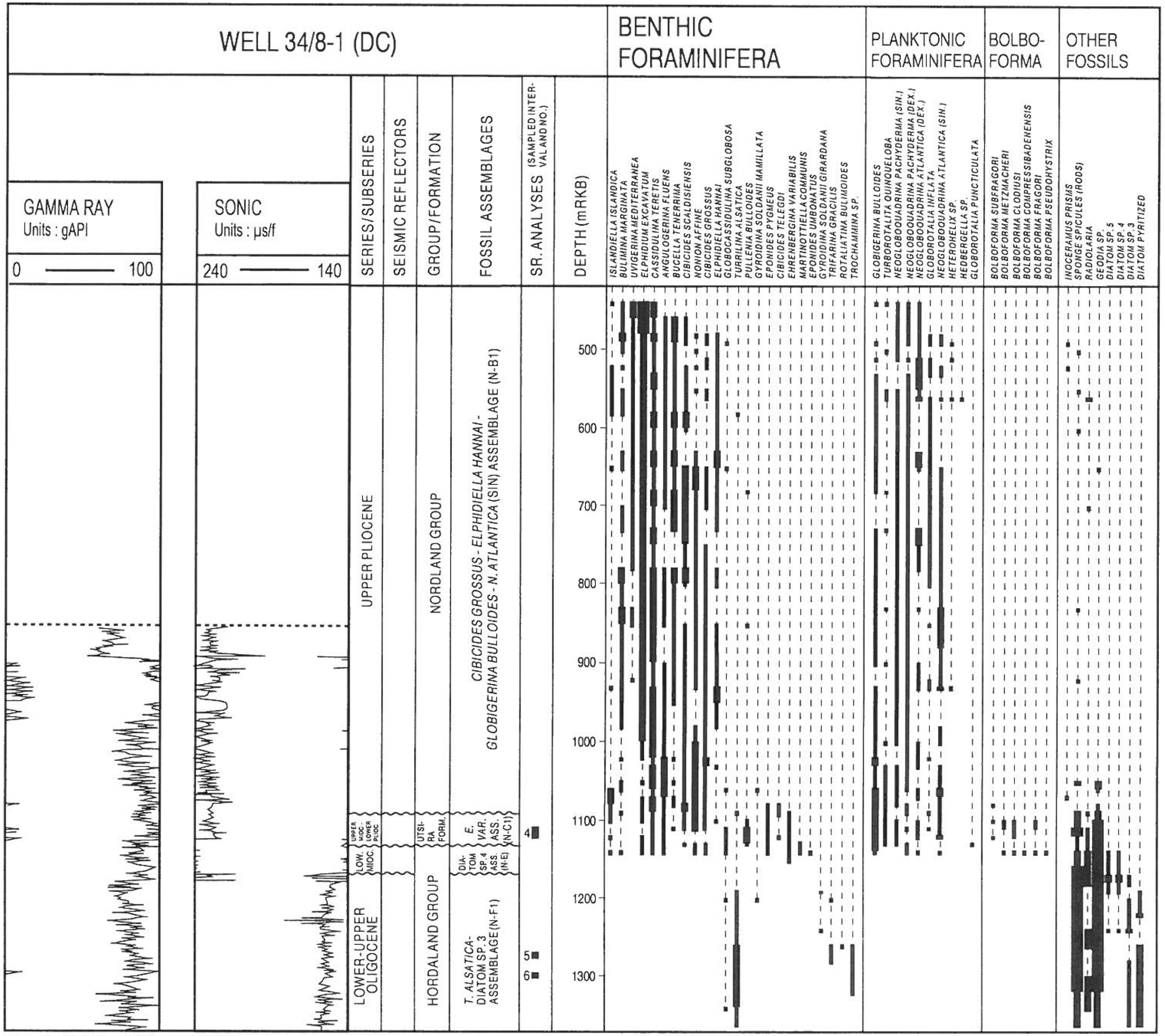
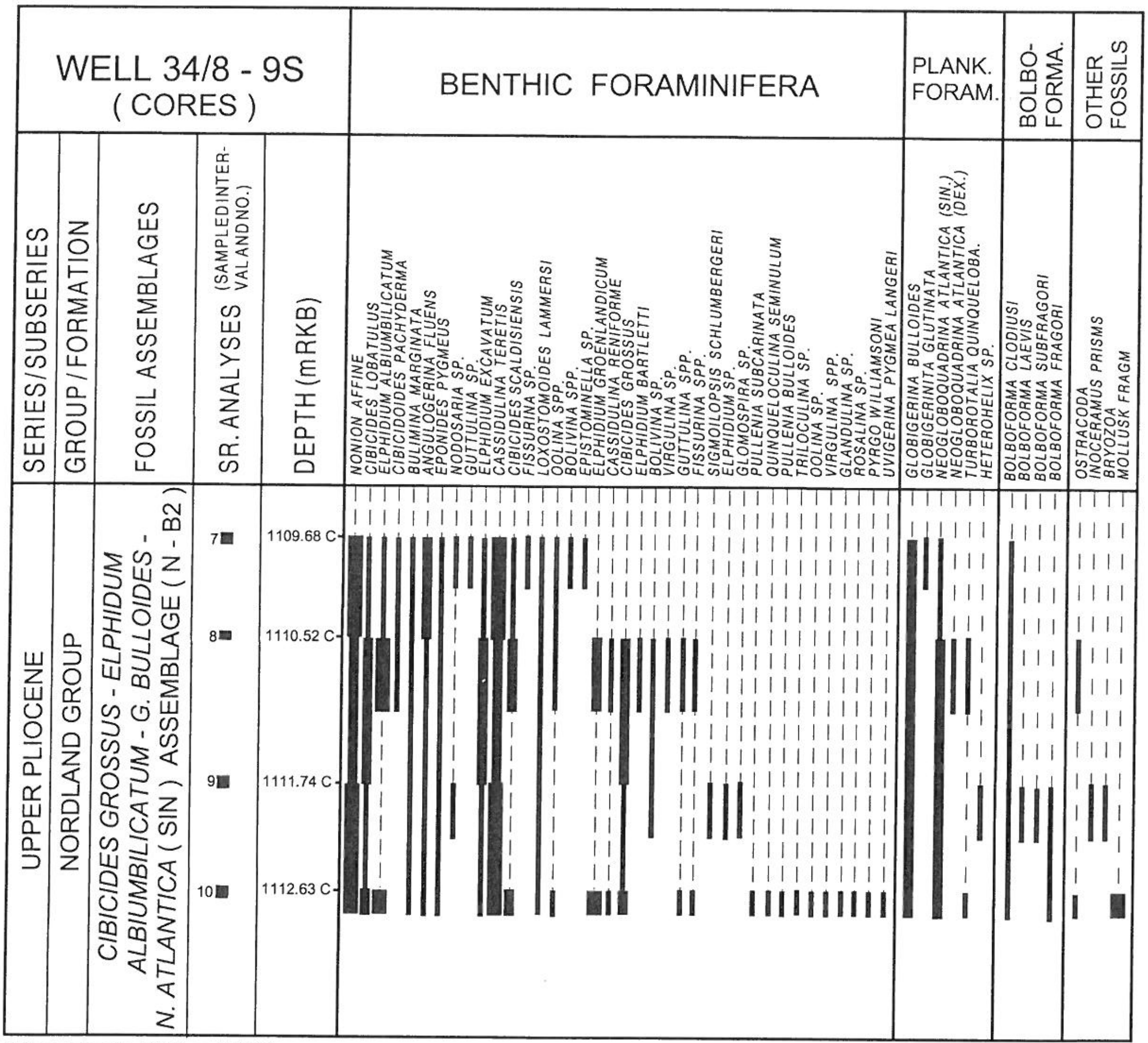

WELL 31/3-1(DC)
BENTHIC FORAMINIFERA
PLANK. FORAM.
OTHER FOSSILS
SERIES/SUBSERIES
SEISMIC REFLECTORS
GROUP/FORMATION
FOSSIL ASSEMBLAGES
SR. ANALYSES (SAMPLED INTERVAL AND NO.)
DEPTH (mRKB)
NONION LABRADORICUM
NONION AFFINE
CIBICIDES LOBATULUS
CASSIDULINA RENIFORME
BULIMINA MARGINATA
UVIGERINA PEREGRINA
ELPHIDIUM EXCAVATUM
HAYNESINA ORBICULARE
CASSIDULINA TERETIS
ANGULOGERINA ANGULOSA
ISLANDIELLA NORCROSSI
BOLIVINA PYGMAEA
BOLIVINA CF. ROBUSTA
ISLANDIELLA HELENAE
VIRGULINA LOEBLICHI
ISLANDIELLA ISLANDICA
PYRGO BULLOIDES
ANGULOGERINA FLUENS
CIBICIDOIDES PACHYDERMA
KARRERIELLA BRADYI
TURRILINA ALSATICA
KARRERIELLA SIPHONELLA
CERATOBULIMINA CONTRARIA
GYROIDINA SOLDANII GIRARDANA
STILOSTOMELLA LONGISCATA
STILOSTOMELLA HIRSUTA
GYROIDINA SOLDANII MAMILLATA
PULLENIA BULLOIDES
ALABAMINA TANGENTIALIS
BULIMINA ALSATICA
ALABAMINA WOLTERSTORFII
STILOSTOMELLA ADOLPHINA
LOXOSTOMUM DIGITALE
TURBOROTALIA QUINQUELOBA
NEOGLOBOQUADRINA PACHYDERMA (SIN.)
NEOGLOBOQUADRINA PACHYDERMA (DEX.)
GLOBOGERINA BULLOIDES
REVORKED FORAMS FROM UPPER CRETAC.
RADIOLARIA
DIATOMS PYRITEZED
PLEISTOCENE
LOWER OLIGOCENE
NORDLAND GROUP
HORDALAND GROUP
NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) ASSEMBLAGE (N-A)
T. ALSATICA - G. SOLDANII MAMILLATA - S. HIRSUTA ASSEM. (N - G)
1
2
3
440
460
480
500
520
540
560
580
Water depth: 343 m (MSL)

Figure 5



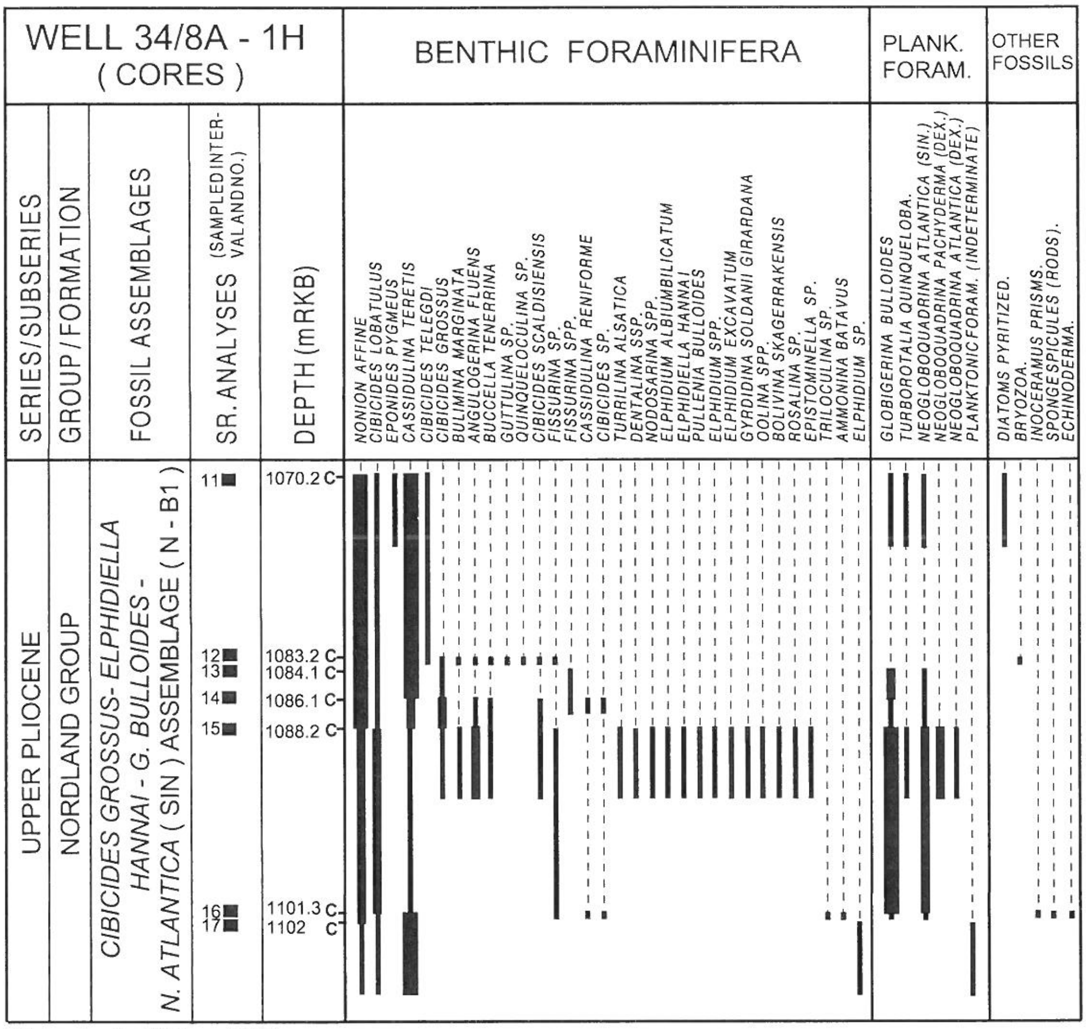
Water depth: 324 m (MSL)

Figure 6



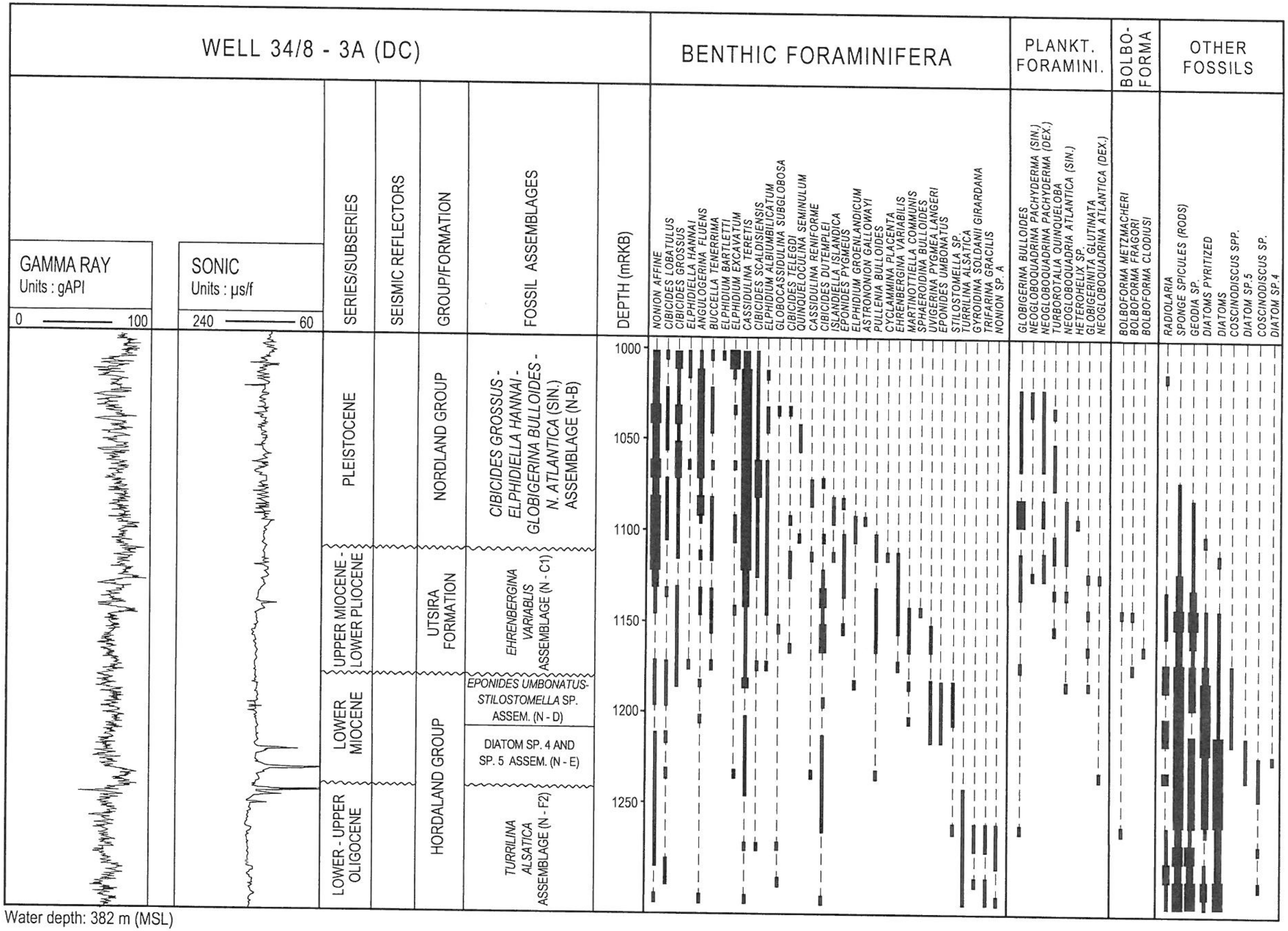
Water depth: 300 m (MSL)

Figure 7



Water depth: 335 m (MSL)

Figure 8



Water depth: 382 m (MSL)

Figure 9

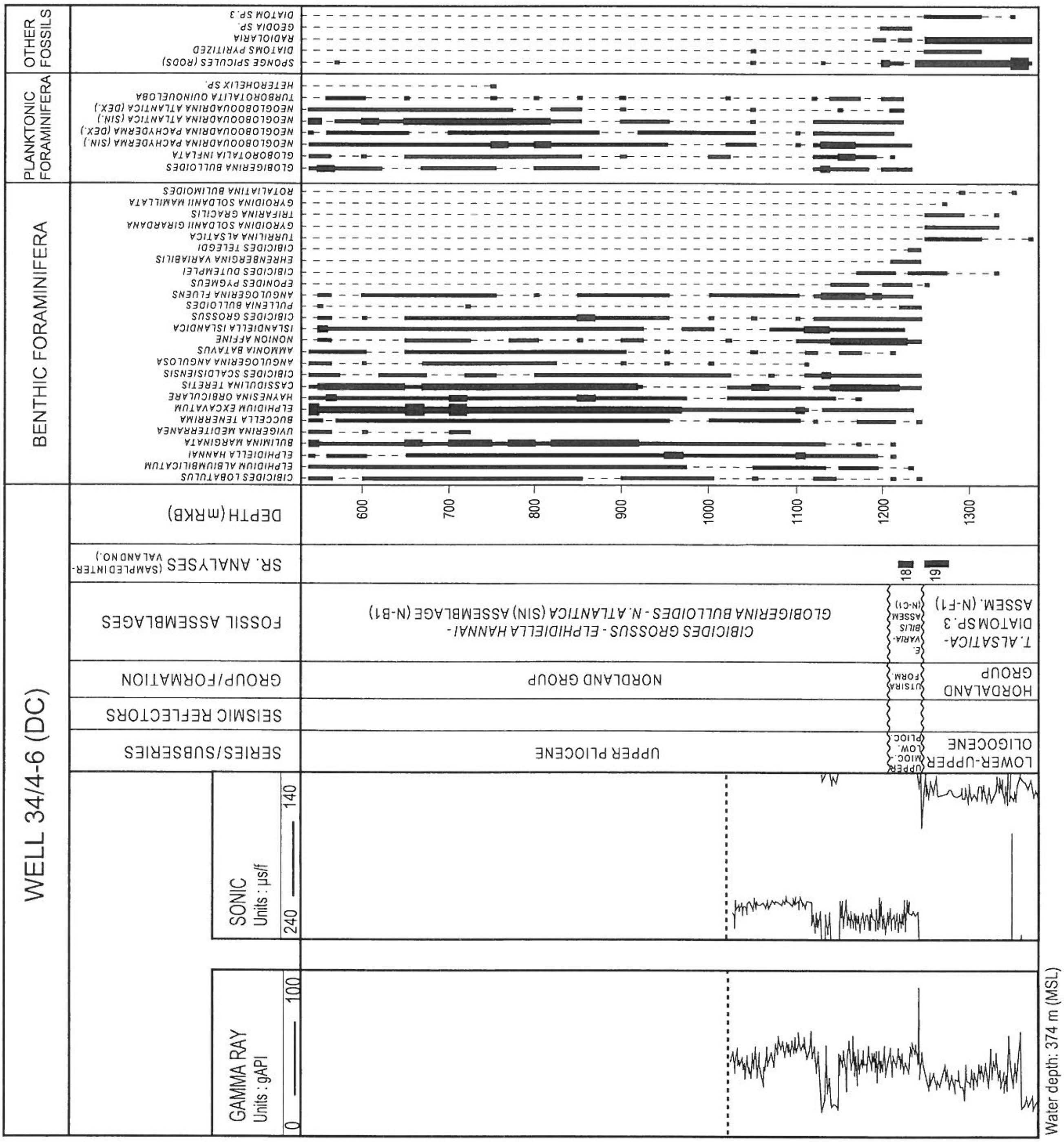

WELL 34/4-6 (DC)
BENTHIC FORAMINIFERA
PLANKTONIC FORAMINIFERA
OTHER FOSSILS
DIATOM SP. 3
GEODIA SP.
RADIOLARIA
DIATOMS PYRITIZED
SPONGE SPICULES (RODS)
HETEROHELIX SP.
TURBOROTALITA QUINQUELOBA
NEOGLOBOQUADRINA ATLANTICA (DEX.)
NEOGLOBOQUADRINA ATLANTICA (SIN.)
NEOGLOBOQUADRINA PACHYDERMA (DEX.)
NEOGLOBOQUADRINA PACHYDERMA (SIN.)
GLOBOROTALIA INFLATA
GLOBIGERINA BULLOIDES
ROTALIATINA BULIMOIDES
GYROIDINA SOLDANII MAMILLATA
TRIFARINA GRACILIS
GYROIDINA SOLDANII GIRARDANA
TURRILINA ALSATICA
CIBICIDES TELEGDI
EHRENBERGINA VARIABILIS
CIBICIDES DUTEMPLEI
EPONIDES PYGMAEUS
ANGULOGERINA FLUENS
PULLENIA BULLOIDES
CIBICIDES GROSSUS
ISLANDIELLA ISLANDICA
NONION AFFINE
AMMONIA BATAVUS
ANGULOGERINA ANGULOSA
CIBICIDES SCALDISIENSIS
CASSIDULINA TERETIS
HAYNESINA ORBICULARE
ELPHIDIUM EXCAVATUM
BUCCELLA TENERRIMA
UVIGERINA MEDITERRANEA
BULIMINA MARGINATA
ELPHIDIELLA HANNAI
ELPHIDIUM ALBIUMBILICATUM
CIBICIDES LOBATULUS
DEPTH (mRKB)
600
700
800
900
1000
1100
1200
1300
SR. ANALYSES (SAMPLED INTERVAL AND NO.)
18
19
FOSSIL ASSEMBLAGES
CIBICIDES GROSSUS - ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES - N. ATLANTICA (SIN) ASSEMBLAGE (N-B1)
E. VARIABILIS ASSEM. (N-C1)
T. ALSATICA - DIATOM SP. 3 ASSEM. (N-F1)
GROUP/FORMATION
NORDLAND GROUP
UTSIRA FORM.
HORDALAND GROUP
SEISMIC REFLECTORS
SERIES/SUBSERIES
UPPER PLIOCENE
UPPER MIOC. LOW. PLIOC.
LOWER-UPPER OLIGOCENE
SONIC
Units : µs/f
240
140
GAMMA RAY
Units : gAPI
0
100
Water depth: 374 m (MSL)

Figure 10

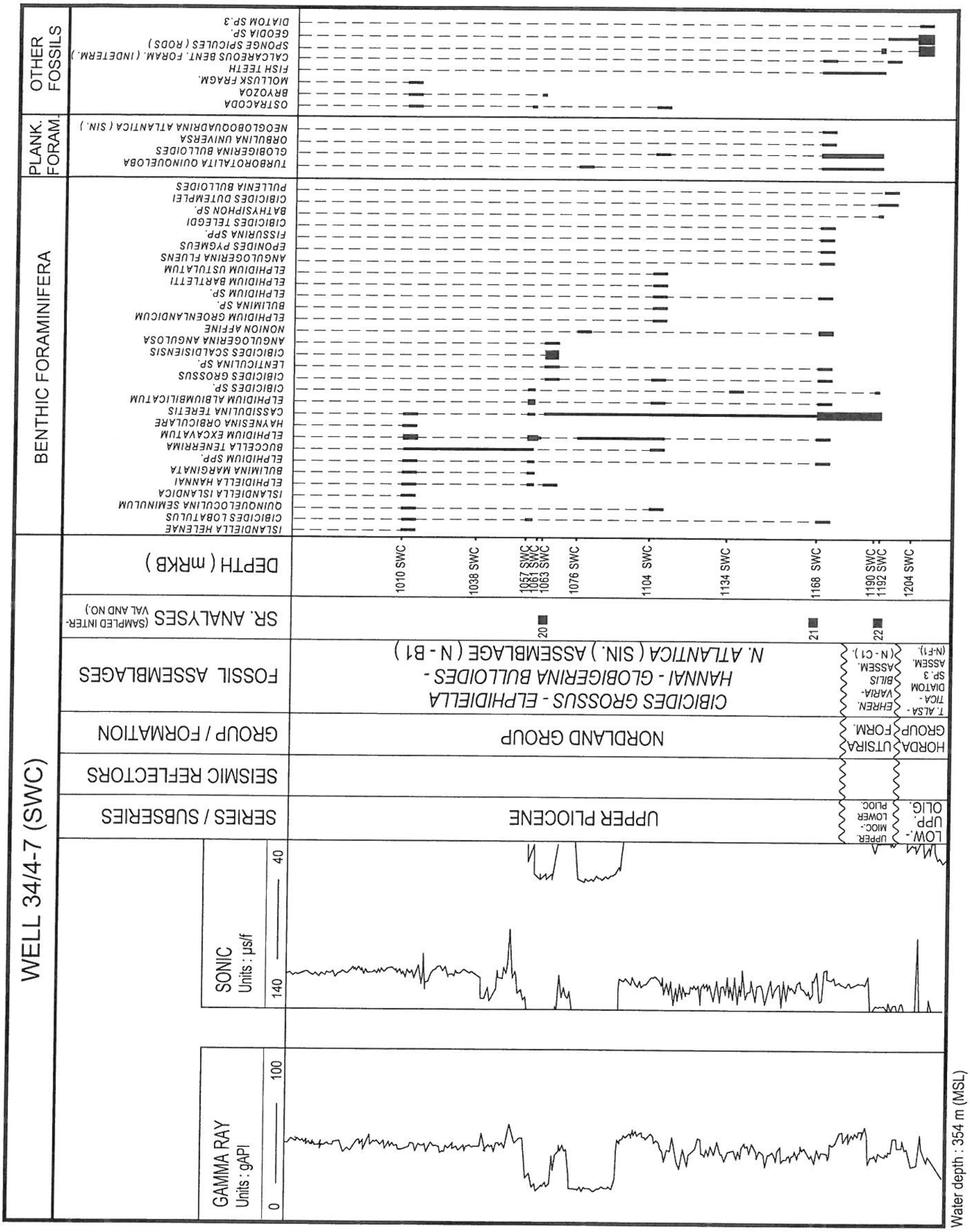

WELL 34/4-7 (SWC)
GAMMA RAY
Units : gAPI
0
100
SONIC
Units : µs/f
140
40
SERIES / SUBSERIES
SEISMIC REFLECTORS
GROUP / FORMATION
FOSSIL ASSEMBLAGES
SR. ANALYSES (SAMPLED INTER-VAL AND NO.)
DEPTH (mRKB)
BENTHIC FORAMINIFERA
PLANK. FORAM.
OTHER FOSSILS
UPPER PLIOCENE
UPPER-MIOC.-LOWER PLIOC.
LOW.-UPP. OLIG.
NORDLAND GROUP
UTSIRA FORM.
HORDA GROUP
CIBICIDES GROSSUS - ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES - N. ATLANTICA (SIN.) ASSEMBLAGE (N - B1)
EHREN. VARIABILIS ASSEM. (N - C1).
T. ALSATICA - DIATOM SP. 3 ASSEM. (N-F1).
20
21
22
1010 SWC
1038 SWC
1057 SWC
1061 SWC
1063 SWC
1076 SWC
1104 SWC
1134 SWC
1168 SWC
1190 SWC
1192 SWC
1204 SWC
ISLANDIELLA HELENAE
CIBICIDES LOBATULUS
QUINQUELOCULINA SEMINULUM
ISLANDIELLA ISLANDICA
ELPHIDIELLA HANNAI
BULIMINA MARGINATA
ELPHIDIUM SPP.
BUCCELLA TENERRIMA
ELPHIDIUM EXCAVATUM
HAYNESINA ORBICULARE
CASSIDULINA TERETIS
ELPHIDIUM ALBUMBILICATUM
CIBICIDES SP.
CIBICIDES GROSSUS
LENTICULINA SP.
CIBICIDES SCALDISIENSIS
ANGULOGERINA ANGULOSA
NONION AFFINE
ELPHIDIUM GROENLANDICUM
BULIMINA SP.
ELPHIDIUM SP.
ELPHIDIUM BARTLETTI
ELPHIDIUM USTULATUM
ANGULOGERINA FLUENS
EPONIDES PYGMEUS
FISSURINA SPP.
CIBICIDES TELEGDI
BATHYSIPHON SP.
CIBICIDES DUTEMPLEI
PULLENIA BULLOIDES
TURBOROTALITA QUINQUELOBA
GLOBIGERINA BULLOIDES
ORBULINA UNIVERSA
NEOGLOBOQUADRINA ATLANTICA (SIN.)
OSTRACODA
BRYOZOA
MOLLUSK FRAGM.
FISH TEETH
CALCAREOUS BENT. FORAM. (INDETERM.)
SPONGE SPICULES (RODS)
GEODIA SP.
DIATOM SP.3
Water depth : 354 m (MSL)

Figure 11a

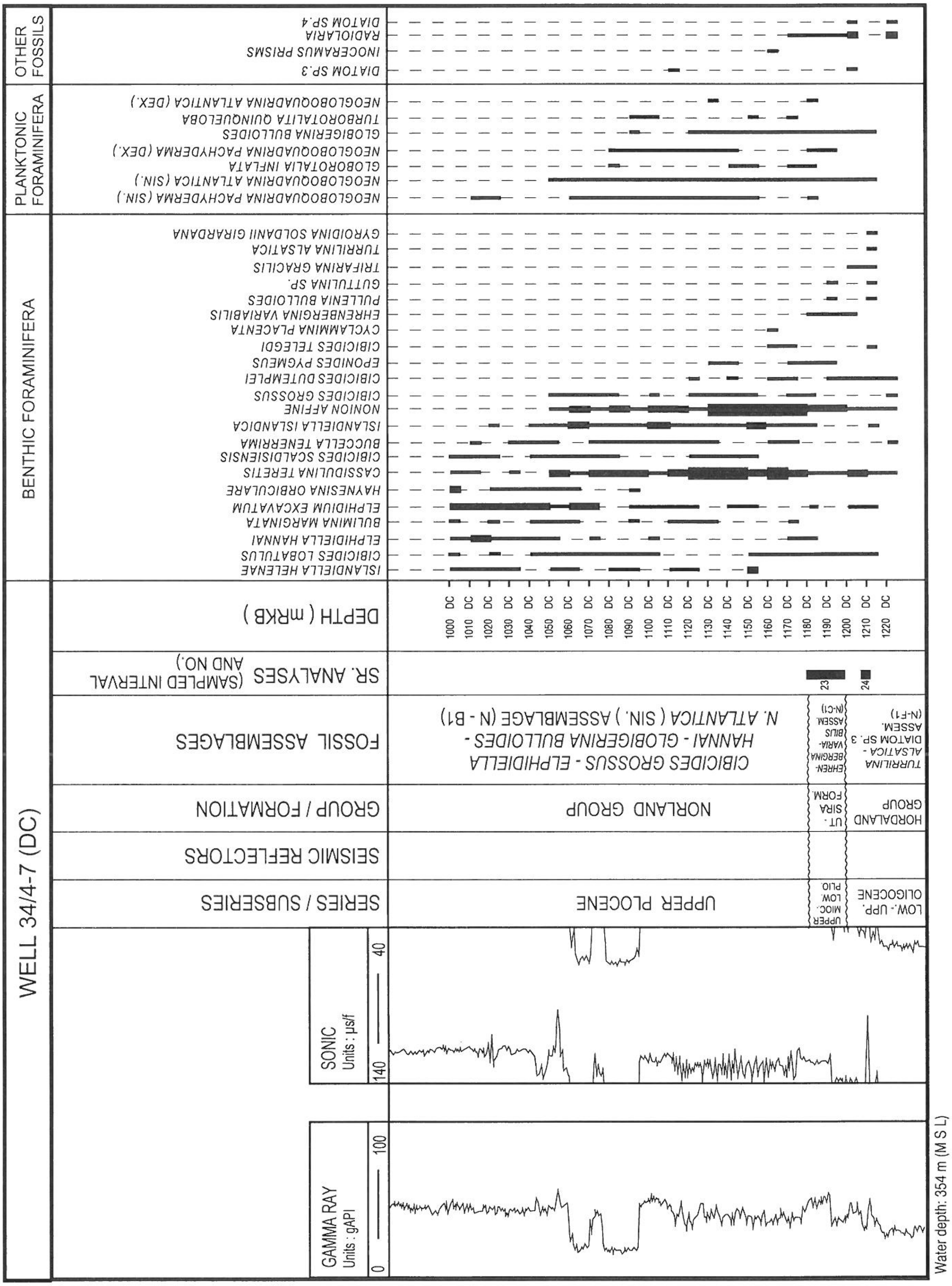

WELL 34/4-7 (DC)
GAMMA RAY Units : gAPI
0
100
SONIC Units : µs/f
140
40
SERIES / SUBSERIES
SEISMIC REFLECTORS
GROUP / FORMATION
FOSSIL ASSEMBLAGES
SR. ANALYSES (SAMPLED INTERVAL AND NO.)
DEPTH (mRKB)
BENTHIC FORAMINIFERA
PLANKTONIC FORAMINIFERA
OTHER FOSSILS
UPPER PLOCENE
UPPER MIOC.- LOW. PLIO.
LOW.- UPP. OLIGOCENE
NORLAND GROUP
UT- SIRA FORM.
HORDALAND GROUP
CIBICIDES GROSSUS - ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES - N. ATLANTICA (SIN.) ASSEMBLAGE (N - B1)
EHREN- BERGINA VARIA- BILIS ASSEM. (N-C1)
TURRILINA ALSATICA - DIATOM SP. 3 ASSEM. (N-F1)
23
24
1000 DC
1010 DC
1020 DC
1030 DC
1040 DC
1050 DC
1060 DC
1070 DC
1080 DC
1090 DC
1100 DC
1110 DC
1120 DC
1130 DC
1140 DC
1150 DC
1160 DC
1170 DC
1180 DC
1190 DC
1200 DC
1210 DC
1220 DC
ISLANDIELLA HELENAE
CIBICIDES LOBATULUS
ELPHIDIELLA HANNAI
BULIMINA MARGINATA
ELPHIDIUM EXCAVATUM
HAYNESINA ORBICULARE
CASSIDULINA TERETIS
CIBICIDES SCALDISIENSIS
BUCCELLA TENERRIMA
ISLANDIELLA ISLANDICA
NONION AFFINE
CIBICIDES GROSSUS
CIBICIDES DUTEMPLEI
EPONIDES PYGMEUS
CIBICIDES TELEGDI
CYCLAMMINA PLACENTA
EHRENBERGINA VARIABILIS
PULLENIA BULLOIDES
GUTTULINA SP.
TRIFARINA GRACILIS
TURRILINA ALSATICA
GYROIDINA SOLDANII GIRARDANA
NEOGLOBOQUADRINA PACHYDERMA (SIN.)
NEOGLOBOQUADRINA ATLANTICA (SIN.)
GLOBOROTALIA INFLATA
NEOGLOBOQUADRINA PACHYDERMA (DEX.)
GLOBIGERINA BULLOIDES
TURBOROTALITA QUINQUELOBA
NEOGLOBOQUADRINA ATLANTICA (DEX.)
DIATOM SP.3
INOCERAMUS PRISMS
RADIOLARIA
DIATOM SP.4
Water depth: 354 m (M S L)

Figure 11b

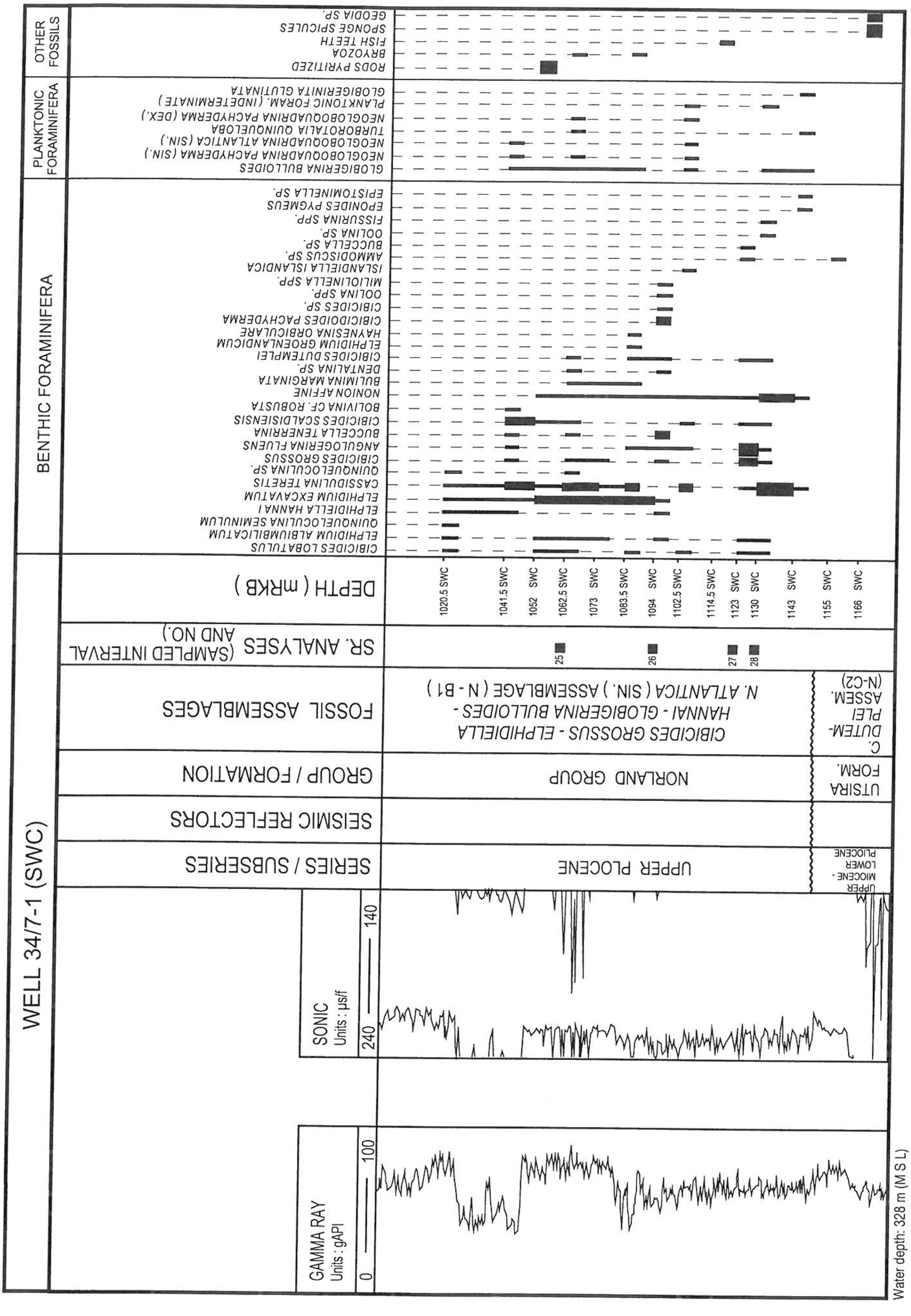
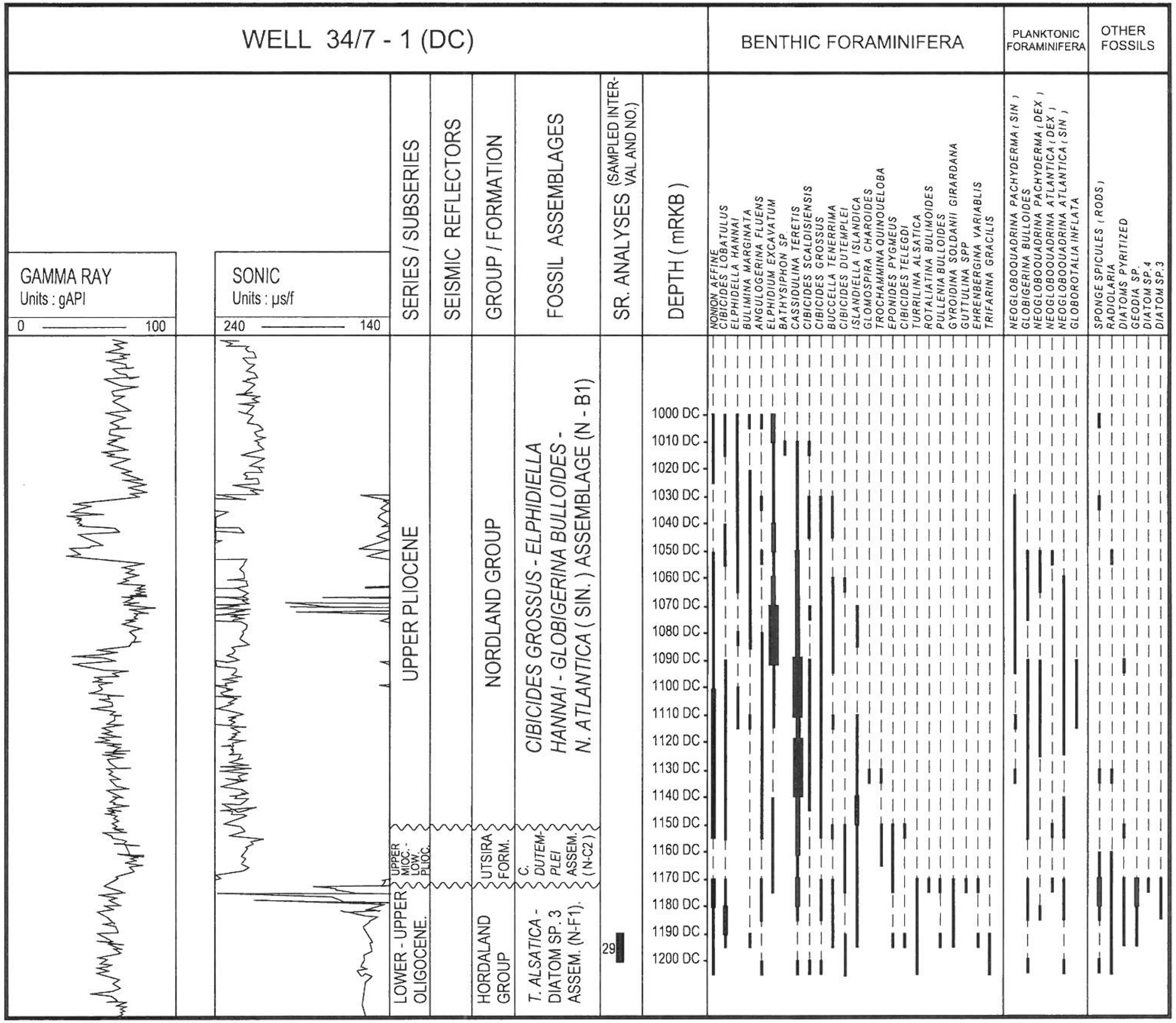
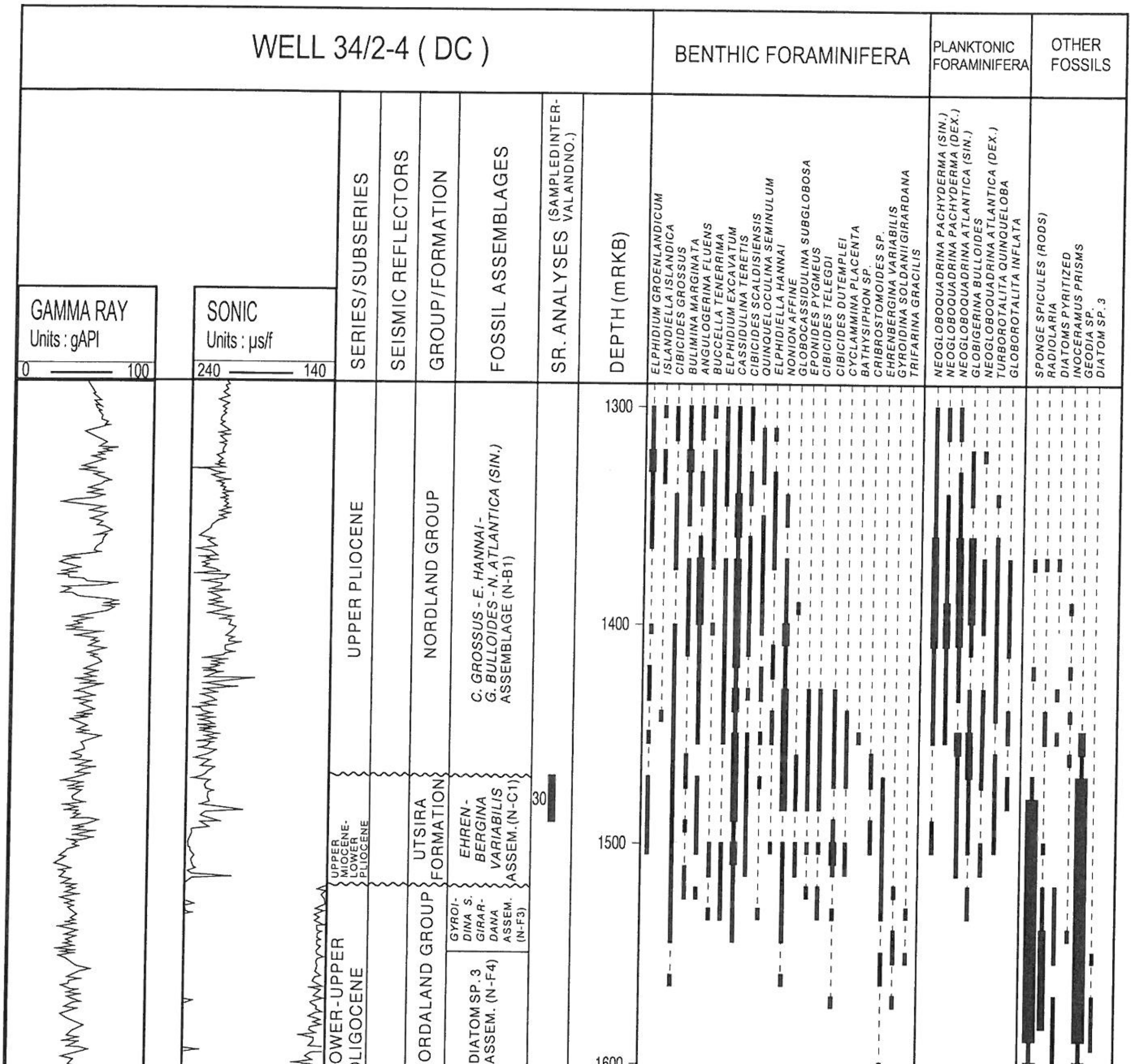

WELL 34/7-1 (SWC)
GAMMA RAY
Units : gAPI
0
100
SONIC
Units : µs/f
240
140
SERIES / SUBSERIES
UPPER PLIOCENE
UPPER MIOCENE - LOWER PLIOCENE
SEISMIC REFLECTORS
GROUP / FORMATION
NORLAND GROUP
UTSIRA FORM.
FOSSIL ASSEMBLAGES
CIBICIDES GROSSUS - ELPHIDIELLA HANNAI - GLOBIGERINA BULLOIDES - N. ATLANTICA (SIN.) ASSEMBLAGE (N - B1)
C. DUTEMPLEI ASSEM. (N-C2)
SR. ANALYSES (SAMPLED INTERVAL AND NO.)
25
26
27
28
DEPTH (mRKB)
1020.5 SWC
1041.5 SWC
1052 SWC
1062.5 SWC
1073 SWC
1083.5 SWC
1094 SWC
1102.5 SWC
1114.5 SWC
1123 SWC
1130 SWC
1143 SWC
1155 SWC
1166 SWC
BENTHIC FORAMINIFERA
CIBICIDES LOBATULUS
ELPHIDIUM ALBUMBILICATUM
QUINQUELOCULINA SEMINULUM
ELPHIDIELLA HANNAI
ELPHIDIUM EXCAVATUM
CASSIDULINA TERETIS
QUINQUELOCULINA SP.
CIBICIDES GROSSUS
ANGULOGERINA FLUENS
BUCCELLA TENERRIMA
CIBICIDES SCALDISIENSIS
BOLIVINA CF. ROBUSTA
NONION AFFINE
BULIMINA MARGINATA
DENTALINA SP.
CIBICIDES DUTEMPLEI
ELPHIDIUM GROENLANDICUM
HAYNESINA ORBICULARE
CIBICIDOIDES PACHYDERMA
CIBICIDES SP.
OOLINA SPP.
MILIOLINELLA SPP.
ISLANDIELLA ISLANDICA
AMMODISCUS SP.
BUCCELLA SP.
OOLINA SP.
FISSURINA SPP.
EPONIDES PYGMEUS
EPISTOMINELLA SP.
PLANKTONIC FORAMINIFERA
GLOBIGERINA BULLOIDES
NEOGLOBOQUADRINA PACHYDERMA (SIN.)
NEOGLOBOQUADRINA ATLANTICA (SIN.)
TURBOROTALIA QUINQUELOBA
NEOGLOBOQUADRINA PACHYDERMA (DEX.)
PLANKTONIC FORAM. (INDETERMINATE)
GLOBIGERINITA GLUTINATA
OTHER FOSSILS
RODS PYRITIZED
BRYOZOA
FISH TEETH
SPONGE SPICULES
GEODIA SP.
Water depth: 328 m (M S L)

Figure 12a



Water depth : 328 m (MSL)

Figure 12b



Water depth: 381 m (MSL)

Figure 13

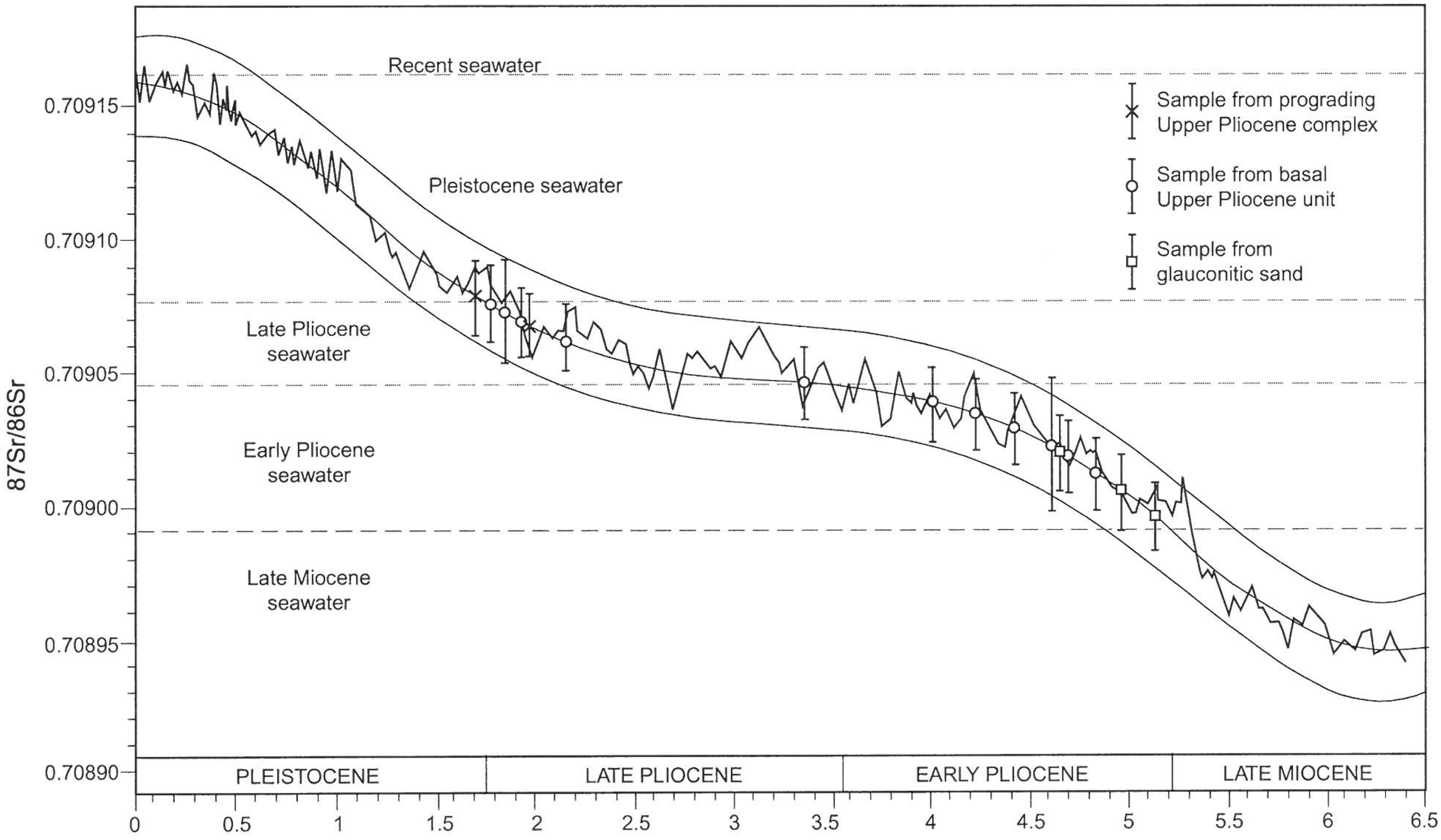

Recent seawater
Pleistocene seawater
Late Pliocene seawater
Early Pliocene seawater
Late Miocene seawater
Sample from prograding Upper Pliocene complex
Sample from basal Upper Pliocene unit
Sample from glauconitic sand
87Sr/86Sr
0.70915
0.70910
0.70905
0.70900
0.70895
0.70890
PLEISTOCENE
LATE PLIOCENE
EARLY PLIOCENE
LATE MIOCENE
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5

Figure 14

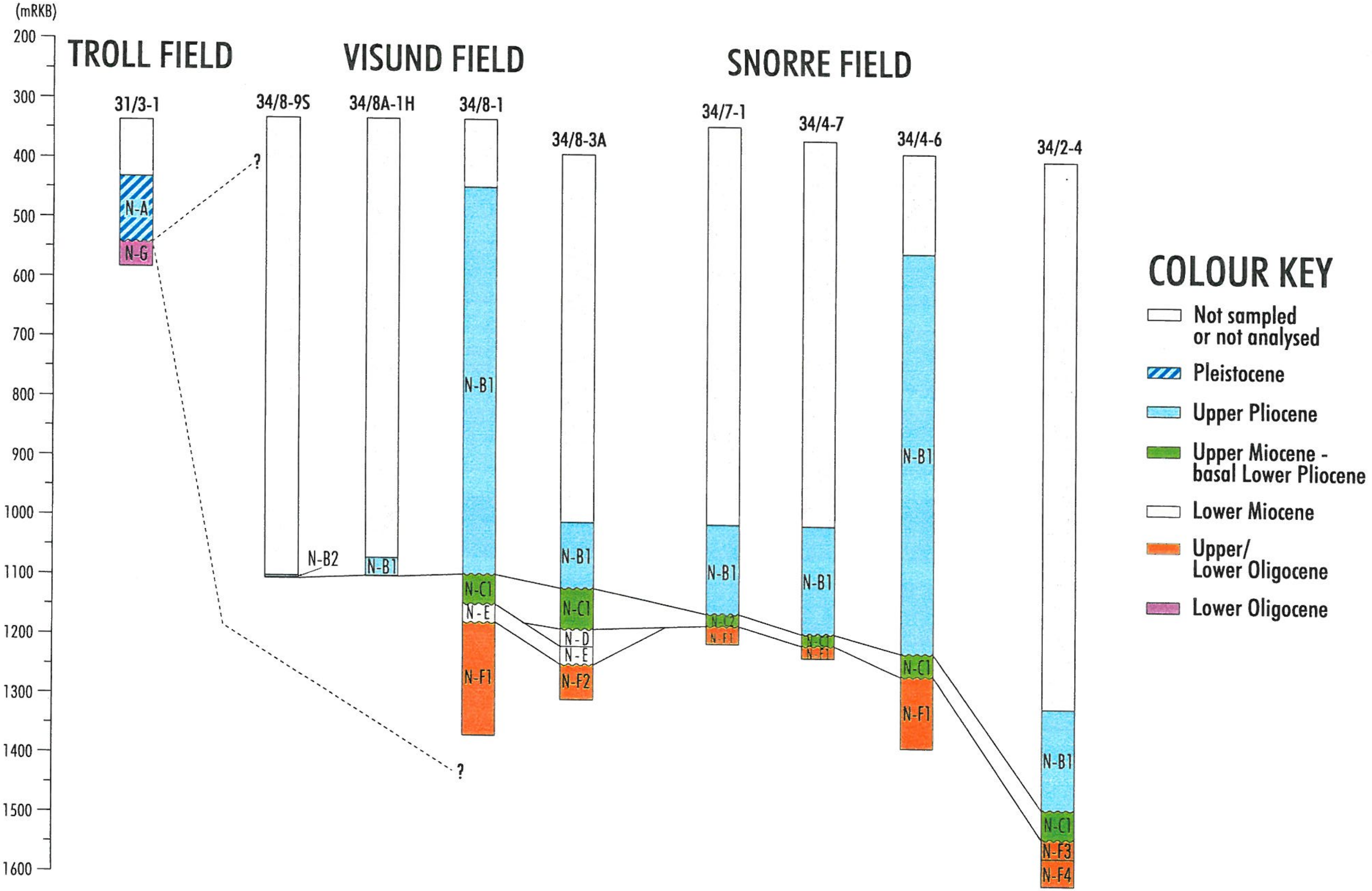

(mRKB)
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
TROLL FIELD
VISUND FIELD
SNORRE FIELD
31/3-1
N-A
N-G
?
?
34/8-9S
N-B2
34/8A-1H
N-B1
34/8-1
N-B1
N-C1
N-E
N-F1
34/8-3A
N-B1
N-C1
N-D
N-E
N-F2
34/7-1
N-B1
N-C2
N-F1
34/4-7
N-B1
N-C1
N-F1
34/4-6
N-B1
N-C1
N-F1
34/2-4
N-B1
N-C1
N-F3
N-F4
COLOUR KEY
Not sampled or not analysed
Pleistocene
Upper Pliocene
Upper Miocene - basal Lower Pliocene
Lower Miocene
Upper/ Lower Oligocene
Lower Oligocene

Figure 15

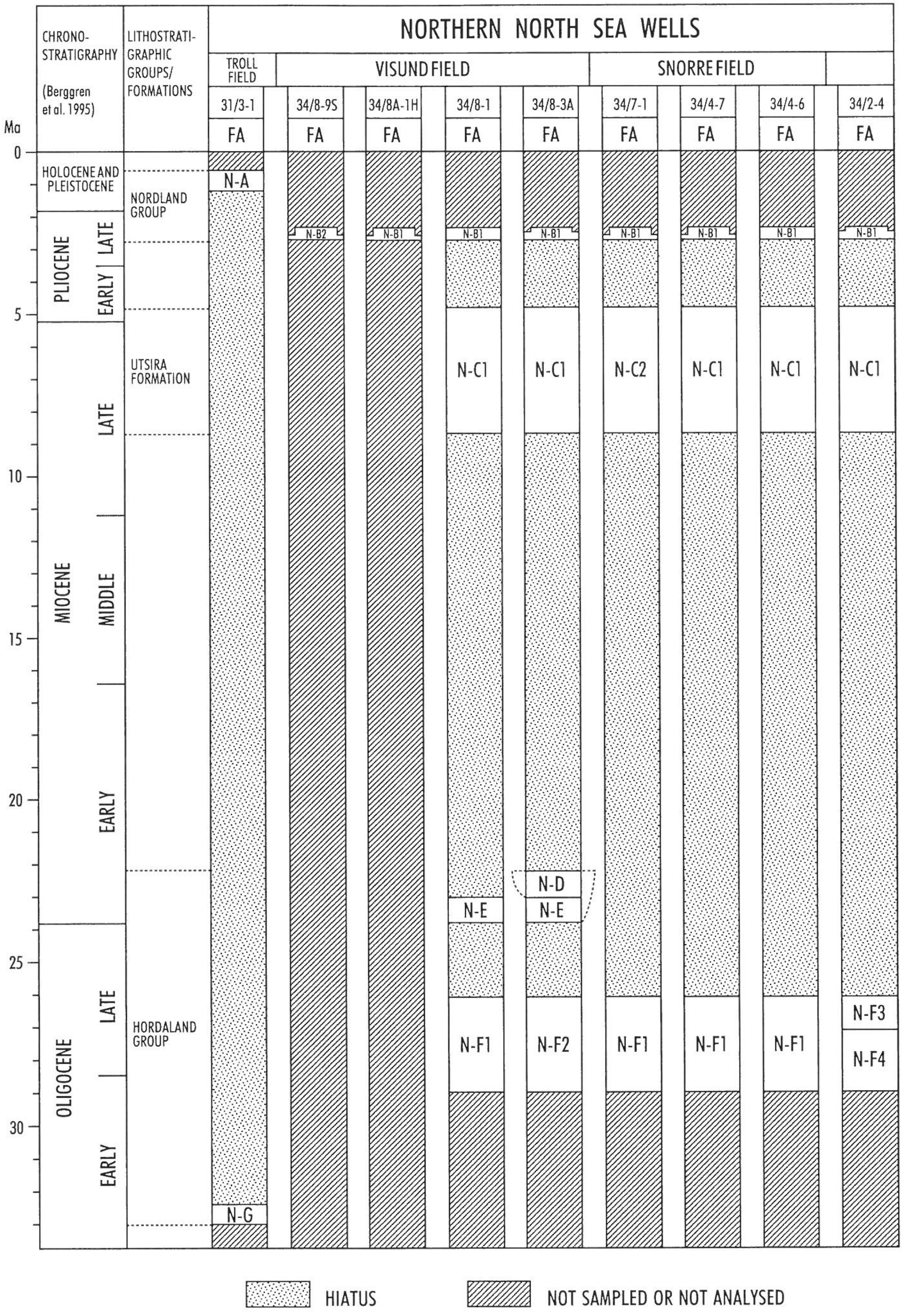
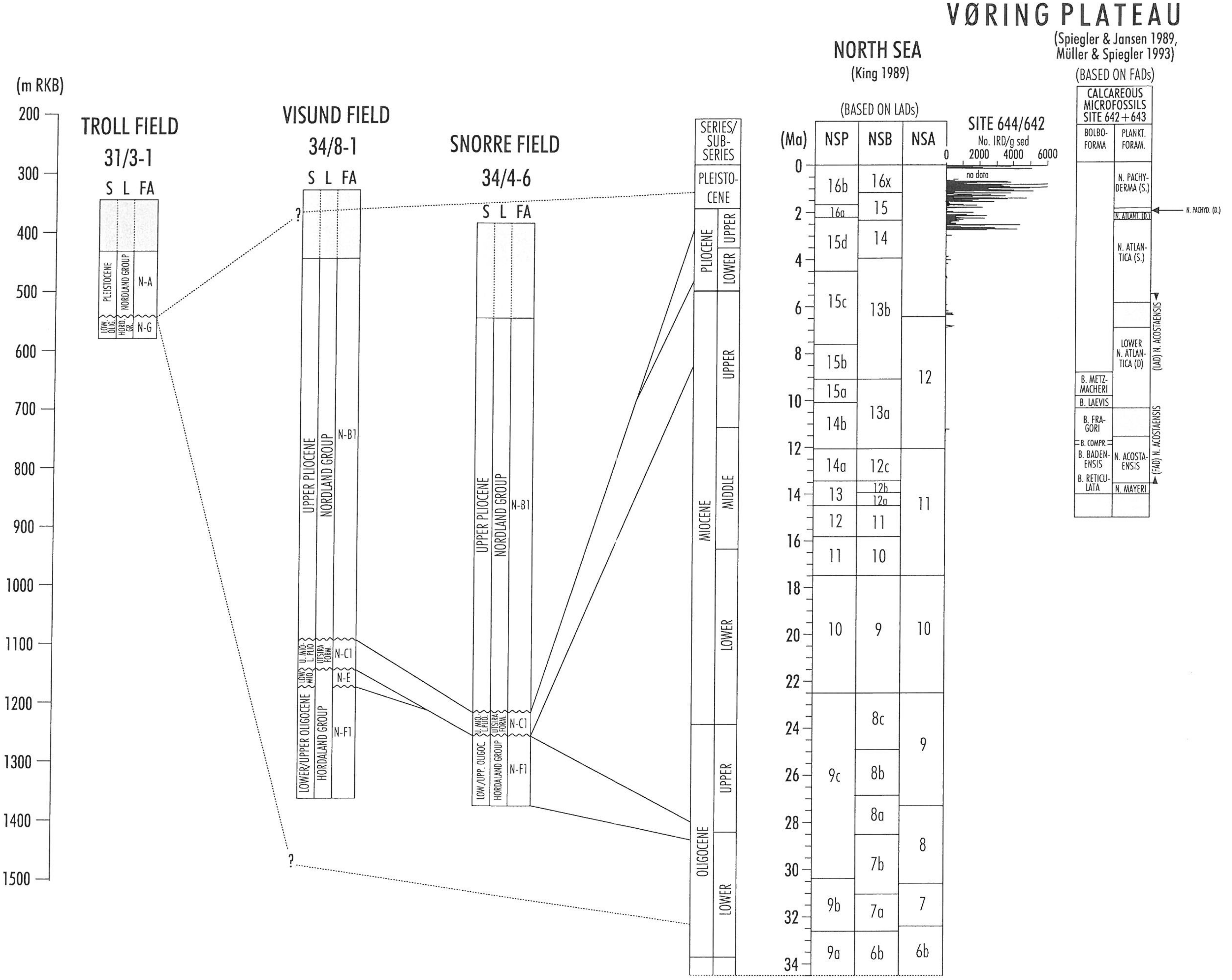

NORTHERN NORTH SEA WELLS
CHRONO-STRATIGRAPHY
(Berggren et al. 1995)
LITHOSTRATI-GRAPHIC GROUPS/ FORMATIONS
TROLL FIELD
VISUND FIELD
SNORRE FIELD
31/3-1
34/8-9S
34/8A-1H
34/8-1
34/8-3A
34/7-1
34/4-7
34/4-6
34/2-4
FA
Ma
0
5
10
15
20
25
30
HOLOCENE AND PLEISTOCENE
PLIOCENE
EARLY
LATE
MIOCENE
LATE
MIDDLE
EARLY
OLIGOCENE
LATE
EARLY
NORDLAND GROUP
UTSIRA FORMATION
HORDALAND GROUP
N-A
N-B2
N-B1
N-C1
N-C2
N-D
N-E
N-F1
N-F2
N-F3
N-F4
N-G
HIATUS
NOT SAMPLED OR NOT ANALYSED

Figure 16



This vertical scale (in Ma) differs from that of the three wells which have metres.

Figure 17

Paper 4:
Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N - 68°N

Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N–68°N

TOR EIDVIN, HARALD BREKKE, FRIDTJOF RIIS & DAVID K. RENSHAW

Eidvin, T., Brekke, H., Riis, F. & Renshaw, D. K.: Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N–68°N. *Norsk Geologisk Tidsskrift*, Vol. 78, pp. 125–151. Oslo 1998. ISSN 0029-196X.

This investigation is based on six exploration wells: 6607/5-1 and /5-2 (Utgard High), 6506/12-4 (Halten Terrace), 6610/7-1, 6610/7-2 and 6610/3-1 (Nordland Ridge). Fifteen informal fauna zones are outlined. Thick, glacially derived Pleistocene and Upper Pliocene prograding shelf deposits extend along the continental margin of the Norwegian Sea. In well 6607/5-1 and 6506/12-4 Upper Pliocene outer to middle shelf deposits lie unconformably on Upper Miocene outer shelf deposits, which are well developed in these areas. A thin interval of Middle Miocene outer shelf sediments is present in well 6607/5-1. This rests unconformably upon Lower/Middle Eocene middle to outer shelf deposits, which in turn rest unconformably upon the Upper Cretaceous. In well 6506/12-4, the Upper Miocene rests unconformably on outer to middle shelf sediments from the Upper Oligocene/Lower Miocene, which in turn lie unconformably on the Lower/Middle Eocene. In well 6607/5-2 Upper Pliocene outer shelf sediments lie unconformably on the Lower/Middle Eocene. Wells 6610/7-1 and /7-2 on the Nordland Ridge penetrate the proximal, oldest parts of the glacially derived prograding sediments of Late Pliocene age, which in this area are middle to inner shelf deposits. In addition, wells 6610/7-1 and 6610/3-1 penetrate underlying Early Oligocene coastal deposits. Lower/Middle Eocene sediments lie below the coastal deposits in well 6610/7-1. In well 6610/7-2 Upper Pliocene deposits lie unconformably upon low oxic deep basin sediments from the Upper Paleocene. Seismic profiles through this area show that the Upper Pliocene glacial deposits onlap the Lower Oligocene coastal deposits.

Tor Eidvin, H. Brekke & F. Riis, Norwegian Petroleum Directorate, PO Box 600, N-4001 Stavanger, Norway; D. K. Renshaw, Statoil a.s., N-4035 Stavanger, Norway.

Introduction

Accurate dating of Cenozoic sediments on the Norwegian Sea continental shelf is important for understanding maturation and migration of hydrocarbons in this area, as well as for understanding the processes that have led to the uplift of Fennoscandia, which is the original source of the sediments.

In all of the hydrocarbon exploration wells in this area, routine biostratigraphic datings have been carried out by consultants commissioned by oil companies. Traditionally, the Cenozoic has not been given high priority, and consequently the dating of these sediments is of variable quality. The correlation of wells based on a variety of consultant-generated data can be problematic, because of the differing taxonomic nomenclature and the contrasting application and interpretation of the data. None of these routine biostratigraphic investigations are publicly available.

The primary objective of this combined biostratigraphic and seismostratigraphic investigation is to date the sediments and main seismic reflectors. The secondary objective is to interpret depositional environments based on microfaunal content. Of the various dating and correlation methods available (Sr-isotope, dinoflagellates, planktonic foraminifers, etc.), an effort was made to apply the most effective methods according to the stratigraphic level under investigation. Emphasis was placed on correlating planktonic fossil fauna with fossil zones from ODP/DSDP drillings in the Norwegian Sea, as these zones are paleomagnetically calibrated.

Wells 6607/5-1 and /5-2 on the Utgard High and Well 6506/12-4 on the Halten Terrace are included in this investigation because they are situated relatively close to the Neogene depocenters (Fig. 1). These wells penetrate the thickest parts of the Upper Pliocene prograding shelf deposits that cover the continental margin of the Norwegian Sea. Upper Miocene deposits are also well developed in these areas. Furthermore, these wells are situated close to the western margin, and the rich planktonic fossil fauna in these wells can readily be correlated to the planktonic fossil zones in the ODP/DSDP drillings in the Norwegian Sea.

Wells 6610/7-1 and /7-2 on the Nordland Ridge were analyzed because they penetrate the proximal and oldest parts of the Upper Pliocene deposits. Wells 6610/7-1 and 6610/3-1 also penetrate underlying Early Oligocene coastal deposits.

All absolute ages are based on Berggren et al. (1985). Fig. 15 shows ages based on Berggren et al. (1985, 1995).

In order to ensure that the results reported here are consistent with electric logs and other technical information, all depths are expressed as meters below the rig floor (m RKB).

Previous work

As mentioned above, all the exploration wells in this area have been analyzed by biostratigraphic consultants. Based on the results from some of these wells Stratlab (1988) published a general biozonation, comprising sediments from Trias to Pleistocene.

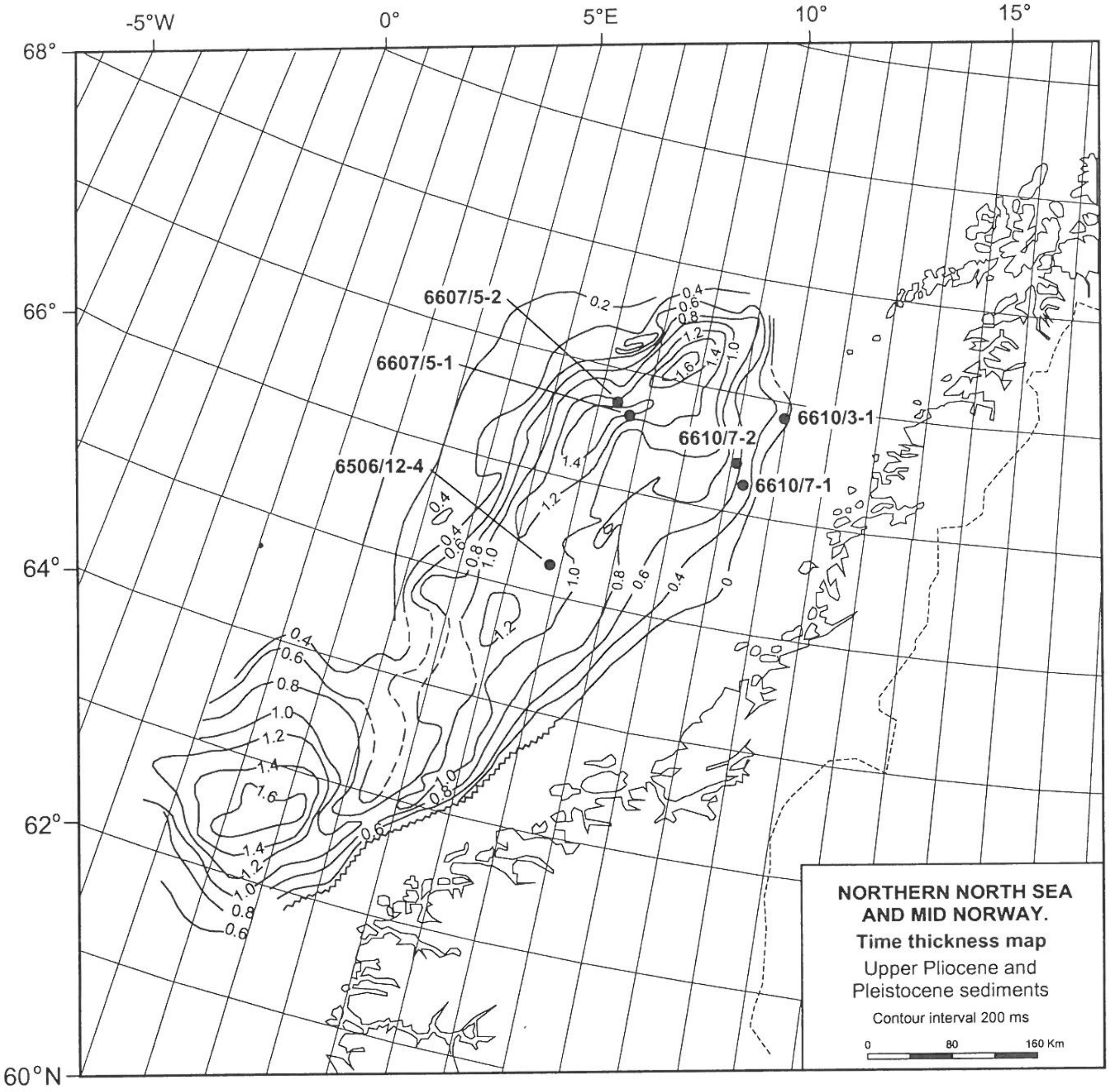


Fig. 1. Location of the wells studied superimposed on an isopach map showing the thickness of the Late Pliocene and Pleistocene sediments in two-way travel time (seconds). Seismic velocity is assumed to be about 2000 m/s in this area, so the thickness measured in kilometers is about the same as the thickness measured in seconds (based on results from Riis & Fjeldskaar 1992). The zigzag line indicates subcropping of Upper Pliocene below Pleistocene.

A general foraminifer zonation of Cenozoic sediments in the North Sea and the Haltenbanken area has been published by Gradstein & Bäckström (1996). This zonation is based on the redating of several exploration wells. Redating of Cenozoic sediments in exploration wells has also been published by Eidvin & Riis (1991) and Poole & Vorren (1993). In this paper we present the results of reanalyses of samples investigated in the two wells in Eidvin & Riis (1991). In addition, the study is extended to include a well on the Utgard High and three wells on the Nordland Ridge.

IKU-Petroleum Research has mapped and sampled outcropping beds in the eastern part of the shelf. The sediments were sampled using a vibracorer and grab at locations having thin Quaternary cover. The ages of these sediments range from Middle Jurassic to Early Neogene. Some of the results of these investigations are published in Bugge (1980), Bugge et al. (1984), Askvik & Rokoengen (1985), Rokoengen et al. (1988) and Gustavson & Bugge (1995).

In connection with geotectonic investigations on the Draugen Field (Haltenbanken), the Pleistocene part of the sequence was sampled in several short conventional cores. Stratigraphic investigations of this material, including paleomagnetic analysis, are published in Haflidason et al. (1991). A geotechnical and seismostratigraphical investiga-

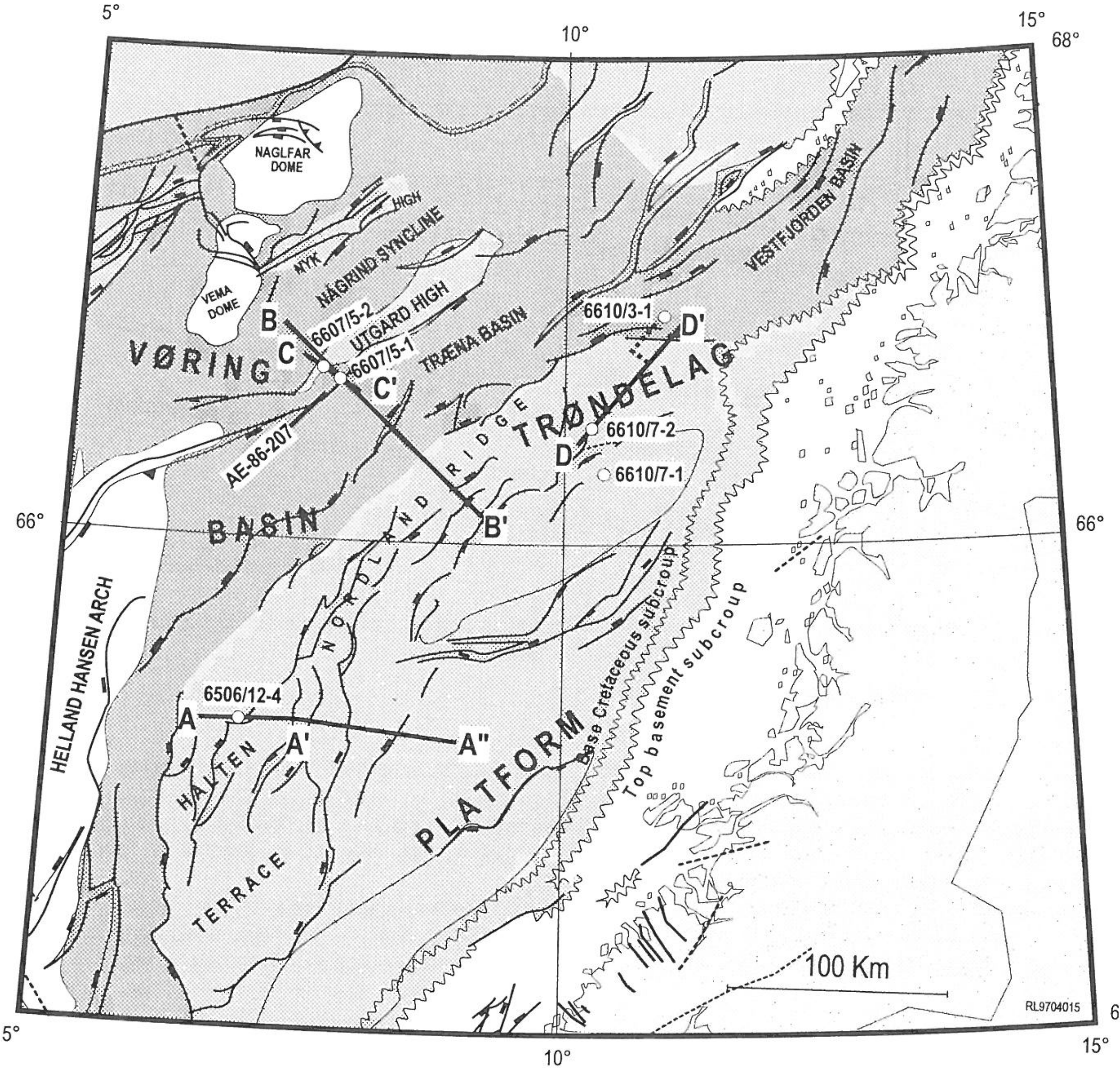


Fig. 2. Map showing wells, seismic lines and major structural elements (modified after Brekke, in press).

tion of Upper Pleistocene sediments on the Smørbukk Field (Haltenbanken) is published by Sættem et al. (1996).

Detailed seismic mapping of the Upper Cenozoic sediments in the Haltenbanken area was published in Rokoengen et al. (1995), and seismic mapping of corresponding sediments in the Nordland Ridge area has been published by Henriksen & Vorren (1996). Seismic mapping of the Upper Pliocene deposits on the Halten Terrace and on the Nordland Ridge was reported in a master's thesis at the University of Oslo (Stuevoll 1989).

Geological setting

The study area

The wells included in this study are situated in two different structural settings. Wells 6607/5-1, 6607/5-2 and 6506/12-4 are situated in the Vøring Basin, which is characterized by an exceptionally thick Cretaceous succession and a complex Cretaceous and Tertiary tectonic history (Blystad et al. 1995; Brekke, in press). Wells 6607/5-1 and 6607/5-2 are situated on the Utgard High which constitutes the eastern flank of the Late

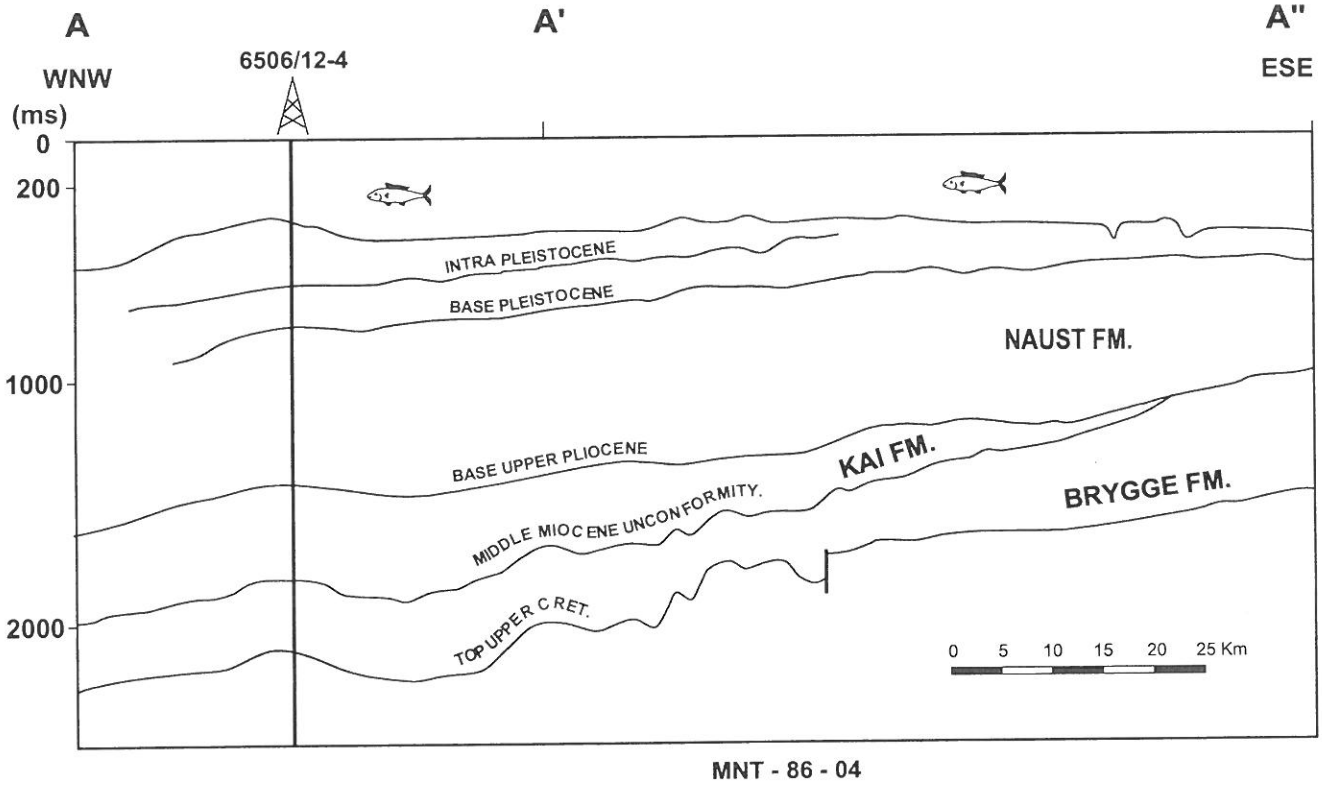


Fig. 3. Digitized seismic line MNT-86-04 through well 6506/12-4.

Cretaceous Någrind Syncline. The wells reveal a very complex and condensed Paleogene and a very thick post-Cenomanian Cretaceous succession. Wells 6610/3-1, 6610/7-2 and 6610/7-1 are situated on the tectonically more stable Late Jurassic/Early Cretaceous Trøndelag Platform (Blystad et al., 1995; Brekke in, press), characterized by a condensed Cretaceous interval and, in places, deeply eroded Tertiary succession (Fig. 2).

Seismic interpretation

The lithostratigraphic nomenclature is after Dalland et al. (1988). The base Naust Formation isopach map shown in Fig. 1 is based on the results of the study by Riis & Fjeldskaar (1992).

In the present study four seismic lines through wells 6506/12-4, 6607/5-1, 6607/5-2 and 6610/7-2 have been interpreted (Figs. 2–7). The interpreted lines on Figs. 3–5 show representative profiles through the Upper Pliocene (Naust Formation) and the Upper/Middle Miocene (Kai Formation) in the central area. The lines on Figs. 6 and 7 show profiles through the proximal part of the Upper Pliocene and the Lower Oligocene coastal deposits (Molo Formation) which is situated under the Upper Pliocene in this area.

The reflector labeled "Base Pleistocene" on profile NRGS-84-470 (Fig. 4) marks the boundary between the underlying prograding Upper Pliocene sequence and the overlying Pleistocene sequence with more parallel and sometimes discontinuous reflectors. Eastwards this reflector truncates the underlying prograding sequence, but at the well site 6607/5-1 no truncation is observed and consequently the reflector is difficult to follow westwards.

The reflector labeled 'Base Upper Pliocene' (Fig. 4) designates the base of the thick prograding sequence. The base of this sequence corresponds to the base of the Naust Formation. Fig. 4 shows that the underlying sequence is truncated further east, and in that area the Naust Formation lies unconformably on Eocene deposits. The underlying layers are truncated at a very low angle in that area and elsewhere. The nature of the reflector varies greatly, but it is recognized in that it is always situated at the base of a large prograding sequence. Often there are parallel reflectors in the underlying sequence, small faults and dome structures. This is not found in the prograding sequence.

Fig. 4 shows a reflector drawn with a dashed line. This reflector marks the boundary between two prograding sequences in the Naust Formation. Eastwards this reflector is truncated by the 'Base Pleistocene' reflector. This is a representative situation for the Naust Formation. The seismic data show a general prograding of beds from east towards west, and internal prograding sequences are truncated by the 'Base Pleistocene' reflector. This indicates that the youngest part of the the Naust Formation is eroded and missing in the eastern part of the area.

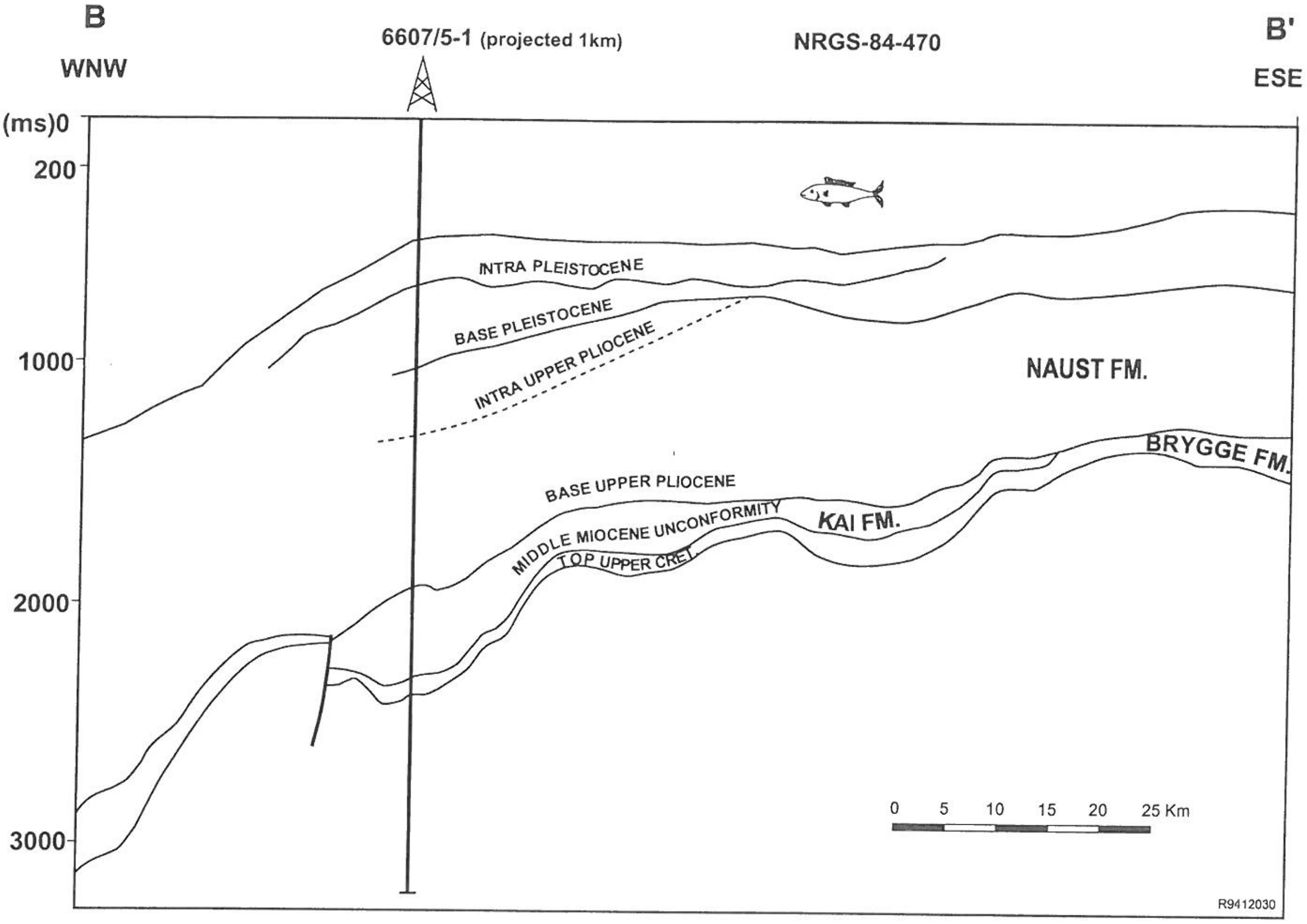


Fig. 4. Digitized seismic line NRGS-84-470. Well 6607/5-1 was tied to line NRGS-84-470 via the intersecting line AE 86-207.

The reflector labeled 'Middle Miocene Unconformity' designates a boundary between two tectonically different situations. The underlying beds (Brygge Formation) have been faulted and folded in dome structures. The overlying beds onlap the boundary. Locally, in the lowermost part of the Upper Pliocene section, some unusually strong and irregular reflectors are observed. Well 6607/5-2 indicates that these reflectors are related to a drop in sonic velocity. Common ocurrrence of the Eocene radiolarian *Cenosphaera* sp. indicates a large amount of reworked material in this part of the Upper Pliocene.

A correlation between wells 6607/5-1 and /5-2 (Fig. 5) shows a complicated pattern of unconformities and hiatuses. It demonstrates that the Paleocene onlaps the top of the Cretaceous from the west towards the east, giving a thinning of the Paleocene towards the east. Between the two wells the top of the Paleocene onlaps the truncated top of the Cretaceous, explaining the missing Paleocene in well 6607/5-1. Strata of Oligocene age are missing in both wells, and the seismic interpretation shows an important erosional unconformity of late Middle Miocene age that also explains the thinning of the Eocene succession between wells 6607/5-2 and 6607/5-1. The interpretation and the dating in well 6607/5-2 show that the Middle Miocene Unconformity is crosscut by the Base Upper Pliocene Unconformity, so that to the west of well 6607/5-2 Upper Pliocene sediments rest directly on Eocene strata, while towards the east the Eocene sequence is separated from the Upper Pliocene sequence by Upper Miocene sediments. This relationship substantiates the tectonic movements in the Early–Middle Miocene and the Late Pliocene which can also be demonstrated throughout the Vøring Basin (Blystad et al., 1995; Brekke, in press).

Profile MNT-86-04 traverses well 6506/12-4 (Fig. 3). The reflectors labeled 'Base Pleistocene' and 'Base Upper Pliocene' are similar to the same reflectors on Fig. 4. However, on Fig. 3 the Naust Formation is truncated at the well site.

The reflector labeled 'Middle Miocene Unconformity' is well developed on profile MNT-86-04 (Fig. 3), because the thickness of the section between this unconformity and the Naust Formation (i.e. the Kai Formation) is much larger in this area. The overlying deposits onlap the unconformity.

Seismic mapping of the base of the Naust Formation shows that the prograding unit has developed a very large sedimentary wedge on the Norwegian Sea continental margin. A similar wedge is developed in the northern North Sea (Fig. 1).

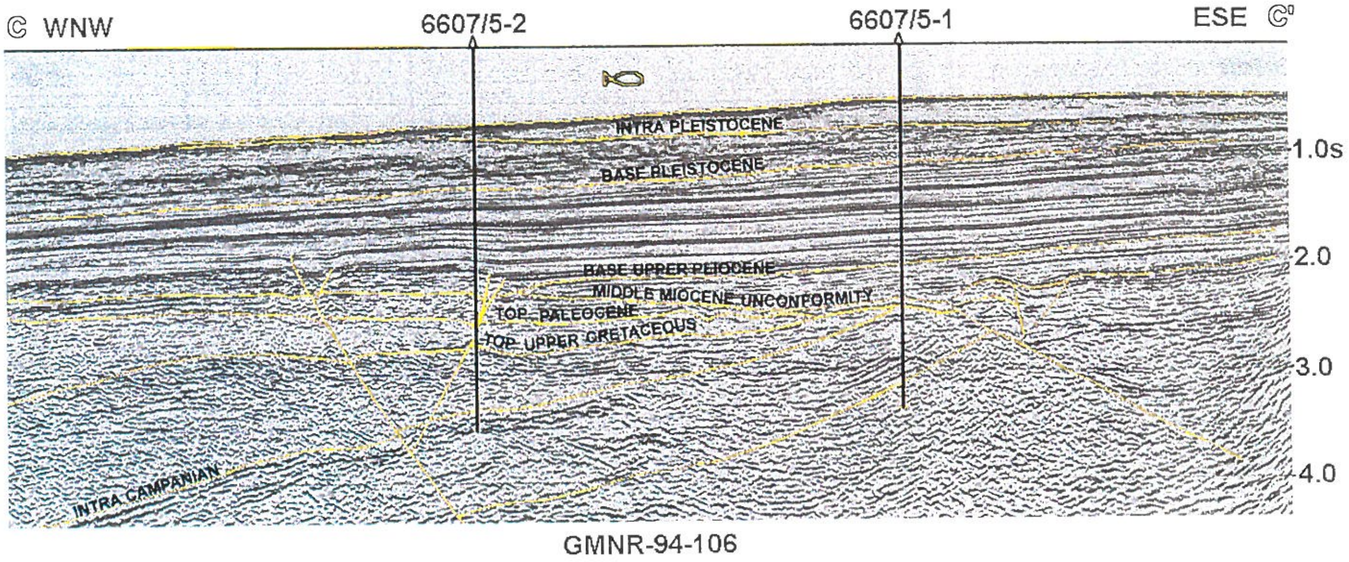


Fig. 5. Interpreted seismic line GMNR-94-106 through well 6607/5-1 and 6607/5-2.

Profiles NRGS-84-470 (Fig. 4) and GMNR-94-106 (Fig. 5) traverse the thickest part of the wedge, while profile MNT-86-04 (Fig. 3) traverses an area with average thickness.

Based on the seismic lines N3-86-315, N3-86-306 and N3-86-314 from the Nordland Ridge, it was possible to correlate the Tertiary strata between wells 6610/3-1 and 6610/7-2 (Fig. 6). The seismic correlation shows that well 6610/7-2 lies west of the Lower Oligocene coastal deposits identified in well 6610/3-1. The coastal deposit sequence is an interval of steeply dipping reflectors interpreted as a set of prograding foresets. The base of the sequence is easily identified on the seismic profiles as a consistent downlap surface. The southwestern side of the sequence can also be readily picked out seismically as an onlap surface where the flat-lying Upper Pliocene stratum in well 6610/7-2 onlaps the prograded front of the coastal deposits (Figs. 6, 7). Eastwards, the deposits thin out due to erosion of the top of the sequence. The erosion left the western boundary as a morphological ramp at the distal forsets (Fig. 6).

Material and methods

Fossil analyses

The biostratigraphic analyses are based largely on ditch-cutting samples. In well 6610/7-1 seven sidewall cores were also available. In well 6610/3-1 only five samples were analyzed and all of these were sidewall cores. Caved material will always be a problem when analyzing ditch cuttings, and consequently the biostratigraphic interpretation and correlation are based mainly on last-appearance data (LADs) of the various taxa. The analyses of the sidewall cores may to some extent reduce the problem of caved material, and in some instances it may be possible to record first-appearance data (FADs).

When drilling with exploration rigs the sampling does not commence before the well has reached a depth of between 100 m and 300 m below the sea floor. Consequently, the upper part of the borehole cannot be analyzed. Ditch cuttings are usually sampled every 10 m in those parts of the wells which are outside the reservoir intervals. In some cases the sampling interval is approximately 5 m. All the available samples are analyzed, but in some thick sequences samples are analyzed at 20-m intervals.

The samples were analysed primarily for planktonic and benthonic foraminifers, but *Bolboforma* (calcareous cysts) were used to establish the stratigraphy in the Middle Miocene–lower part of the Upper Miocene. In the Lower–Upper Oligocene and in the Upper Paleocene pyritized diatoms were used, and in the Lower/Middle Eocene radiolarians were used. The Lower Oligocene section in wells 6610/7-1 and 6610/3-1 was analysed for dinoflagellates in addition to foraminifers.

For analyses of the drill-cuttings samples, 50 g–100 g of material was used. Less material was available from the sidewall cores (10 g–30 g). Unconsolidated material was soaked in water and wet sieved and consolidated material was dissolved in diluted hydrogen peroxide. The identifications were carried out on the 0.1–0.5 mm fraction. In some cases the fractions larger than 0.5 mm and less than 0.1 mm were also studied. In the sidewall cores, material finer than 0.1 mm was saved for palynological analysis. Whenever possible, 300 individuals were picked from each sample. In order to better identify the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity-separated in heavy liquid. Consequently, in fossil-rich samples, 1000–1500 individuals were analyzed. The stratigraphically important fossils are reported in the range charts in Figs. 8a–13.

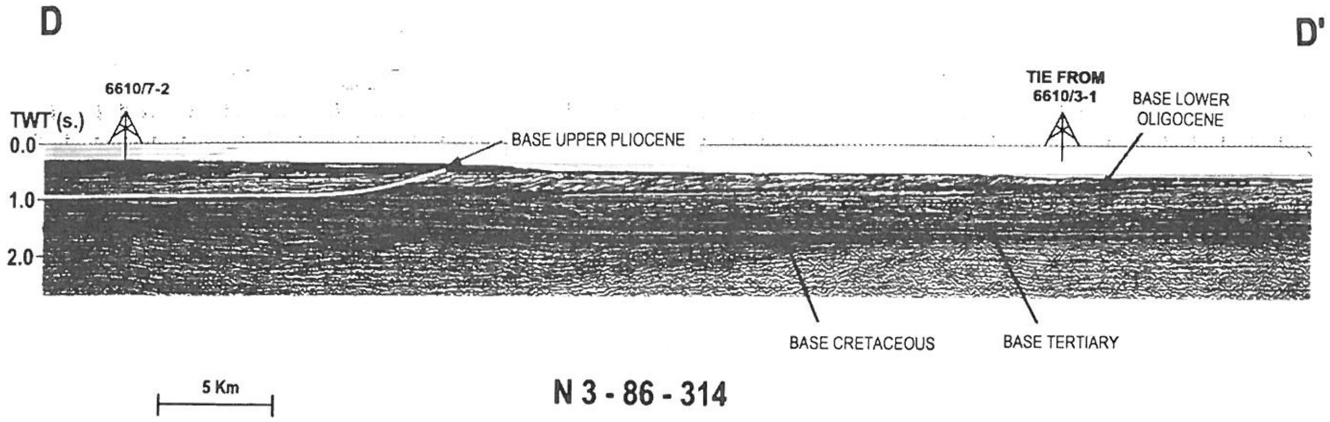


Fig. 6. Interpreted seismic line N3-86-314 through well 6610/7-2 showing the Lower Oligocene coastal deposits.

Strontium isotope analyses

Strontium isotope analyses were performed by the Institute for Energy Technology, Kjeller, Norway, on calcareous material (i.e. tests of calcareous benthic foraminifera) from two sidewall cores representing different stratigraphic levels in well 6610/3-1. Ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$-ratio to a global strontium isotope curve. The curve compiled by the Institute for Energy Technology is based on data from DePaolo (1986), DePaolo & Ingram (1985), Hess et al. (1986), Hodell et al. (1989, 1990, 1991), Koepnick et al. (1985) and Palmer & Elderfield (1985).

Lithologic studies

The lithologic analyses are based on a visual examination of both the samples prior to treatment, and the dispersed and fractionated material after preparation. Owing to the problem of caved material, only a rough description was deemed appropriate.

Biozonation

The standard Cenozoic biostratigraphic scale is based on planktonic foraminifers and calcareous nannoplankton zonations established for tropical and subtropical areas. Towards the north the assemblages become progressively less diverse, and many key species are missing in the Norwegian and the North Seas (King, 1983).

In this work the biozonation broadly follows that of King (1983, 1989) where a micropaleontological zonation for Cenozoic sediments of the North Sea is outlined. Gradstein & Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken and Stratlab's (1988) faunal zonation for the Mid-Norwegian continental shelf are also used extensively. In addition, a number of articles that describe benthonic foraminifers from onshore basins from the area surrounding the central and southern North Sea are used. Since the North Sea zonations cannot be applied in full on the Mid-Norwegian continental shelf, the zonations of planktonic foraminifers (Spiegler & Jansen 1989) and *Bolboforma* (Quale & Spiegler 1989), established through ODP/DSDP drillings in the Norwegian Sea, are very important for dating shelf sediments. Correlation with these zones may also yield quite accurate ages, since the zones are calibrated using nannoplankton and paleomagnetic data (Müller & Spiegler 1993). However, the zonations of King (1983, 1989), Gradstein & Bäckström (1996) and Stratlab (1988) are based on last-appearance data of the various taxa. The zonation of planktonic foraminifers and *Bolboforma* from the ODP/DSDP drillings is based on the first-appearance data.

Biozones

In the six wells examined in this study a system of 15 informal biozones is employed (M–A to M–O); M = Mid-Norway (Figs. 8a–15). The zones are primarily range zones based on the highest occurrence of selected taxa which have been chosen because of their chronostratigraphic importance. In other words, the selected taxa have well-documented, consistent ranges on a regional scale. The individual range zones comprise both planktonic and benthonic forms. Range zone definitions based on a combination of planktonic and benthonic forms are applicable on a regional scale where planktonic/benthonic ratios are often highly variable. We define these zones as follows:

WELL 6607/5-1 (66°38′N, 7°32′E)

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) – *NONION LABRADORICUM* ZONE

Category: Informal partial range zone.

Designation: M–A.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (920 m) and probably to near the sea floor. The base of the zone is marked by the highest occurrence of *Cibicides grossus*.

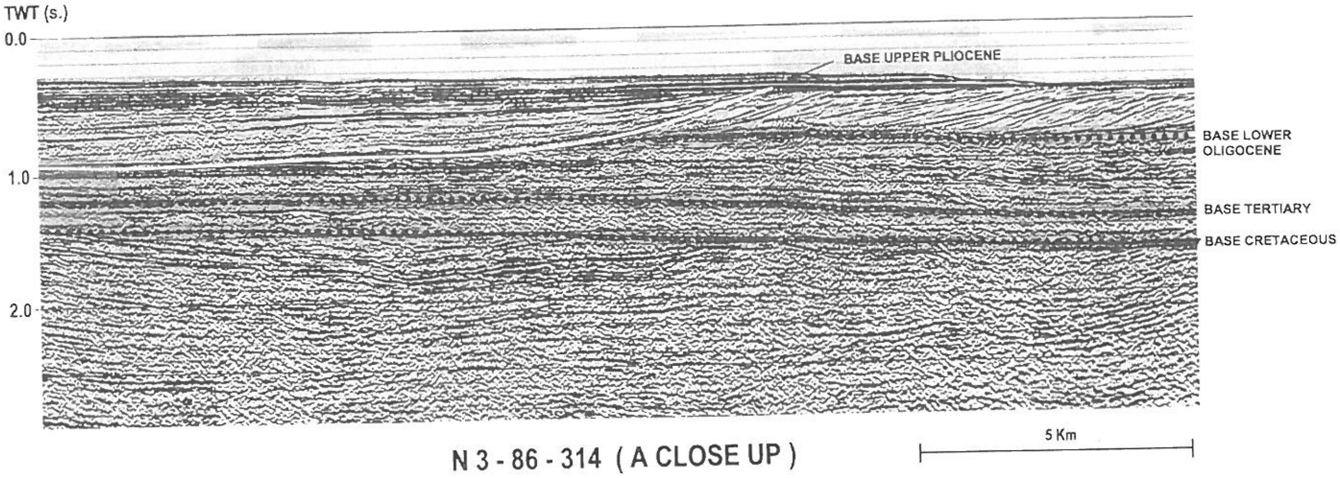


Fig. 7. Interpreted seismic line N3-86-314. A close up which shows that Upper Pliocene prograding deposits onlap the Lower Oligocene coastal deposits.

Depth range: 920 (uppermost investigated sample)–960 m.

Age: Pleistocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzone NSB 16x of King (1989), Zone NSR 13 of Gradstein & Bäckström (1996) and *Neogloboquadrina pachyderma* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna consisting mainly of calcareous foraminifera. *Elphidium excavatum* and *Cassidulina reniforme* occur most frequently. Other characteristic forms are: *Nonion labradoricum*, *Cassidulina teretis*, *Virgulina loeblichi*, *Elphidium albiumbilicatum*, *Bulimina marginata*, *Haynesina orbiculare* and *Cibicides scaldisiensis* (Fig. 8a).

Planktonic foraminifers are represented by *N. pachyderma*. Both encrusted and unencrusted varieties of the sinistrally coiled individuals have been registered.

Remarks: *N. pachyderma* (sinistral, encrusted) has its first frequent occurrence at 1.7 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). This test morphology occurs only sporadically in older sediments. *N. labradoricum* also appears to be restricted to Pleistocene deposits on the Norwegian shelf. King (1989) employs *N. labradoricum* as the nominate taxon for the Pleistocene Subzone NSB 16x of the northern North Sea. The base of Zone M–A coincides with a weak seismic reflector which probably represents a minor hiatus.

CIBICIDES GROSSUS ZONE

Category: Informal partial range zone.

Designation: M–B.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *Cibicides grossus*. The base of the zone is marked by the highest occurrence of *Neogloboquadrina atlantica* (sinistral).

Depth range: 960–1220 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzone NSB 15b of King (1989), Zone NSR 12 of Gradstein & Bäckström (1996), C. grossa zone of Stratlab (1988) and possible *N. pachyderma* (dextral) zone and upper *N. atlantica* (dextral) Zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich fauna of benthonic calcareous foraminifers. *E. excavatum* and *C. reniforme* appear frequently throughout the entire sequence. *C. scaldisiensis* and *C. teretis* are frequent in the lower part of the sequence. Other important species are: *C. grossus*, *V. loeblichi*, *E. albiumbilicatum*, *Buccella frigida*, *B. marginata*, *Nonion affine*, *Cibicidoides pachyderma*, *Angulogerina fluens* and *Uvigerina peregrina* (Fig. 8a).

Planktonic foraminifera are represented by both encrusted and unencrusted forms of *N. pachyderma* (sinistral), which are comparatively frequent throughout the sequence. *N. pachyderma* (dextral) is scarce throughout. *Turborotalita quinqueloba*, *Globigerina bulloides* and *Globorotalia inflata* are found in small numbers in some intervals.

Remarks: With the exception of *C. grossus* all the benthonic foraminifera are extant species. According to King (1989) *C. grossus* is found in the northern North Sea in Upper Pliocene to Lower Pleistocene deposits. In the southern parts of the North Sea it becomes extinct somewhat earlier, close to the Pliocene/Pleistocene boundary. King (1989) establishes the time for the LAD of *C. grossus* in the northern North Sea by registering its LAD above the FAD of *N. pachyderma* (sinistral, encrusted). The FAD of *N. pachyderma* (sinistral, encrusted) at about 1.7 Ma (Spiegler & Jansen 1989) is a good marker for top Upper Pliocene, but this biostratigraphic event is difficult to observe in drill cuttings.

While working with this kind of material, the LAD occurrence of *C. grossus* is the biostratigraphic event closest to the Upper Pliocene/Pleistocene boundary. This applies to the northern North Sea and probably also to the area offshore Mid-Norway.

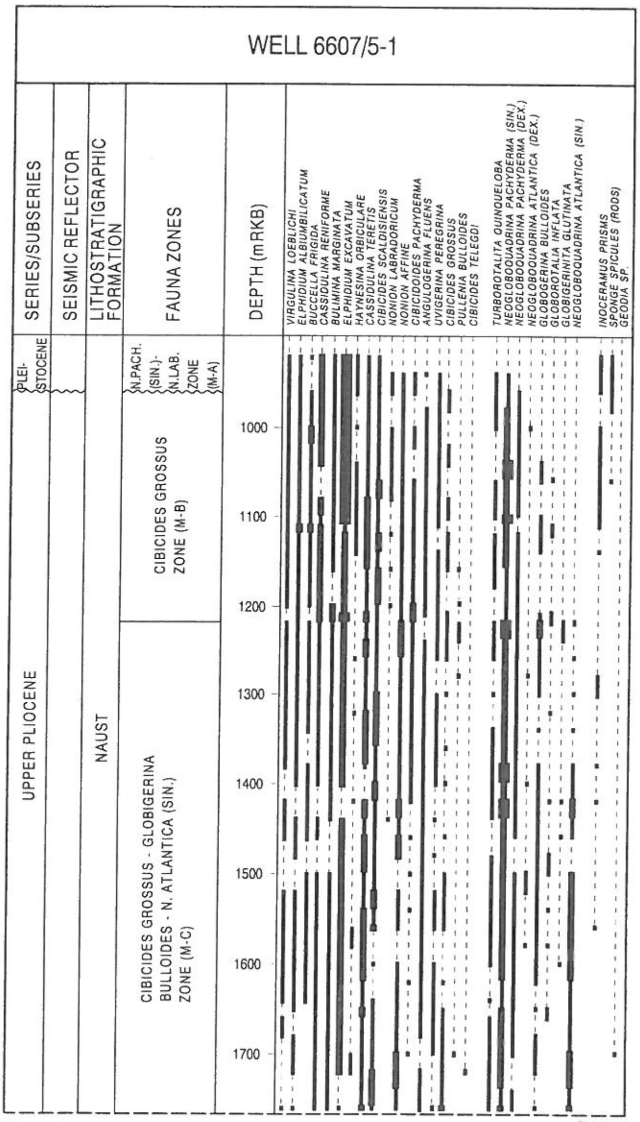
CIBICIDES GROSSUS–GLOBIGERINA BULLOIDES–NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–C.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *N. atlantica* (sinistral). The base of the zone is marked by the highest consistent occurrence of *N. atlantica* (dextral).

(a)



Water depth: 366 M (MSL)

Fig. 8(a).

Depth range: 1220–2020 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. The fauna is relatively uniform throughout the entire sequence. *E. excavatum*, *C. teretis* and *C. scaldisiensis* all occur frequently throughout. *C. grossus* occurs frequently in the lower part of the sequence, but is less common in the upper part. Other species are *N. affine*, *C. reniforme*, *B. marginata* and *B. tenerrima* (Fig. 8a, b).

Planktonic foraminifera are represented by both encrusted and unencrusted forms of *N. pachyderma* (sinistral). Both this species and *N. atlantica* (sinistral) are similarly frequent throughout the sequence. *N. pachyderma* (dextral), *G. bulloides* and *T. quinqueloba* also occur throughout, but in smaller numbers. *G. inflata*, *G. glutinata* and *N. atlantica* (dextral) are found in some intervals.

Remarks: The LAD of *N. atlantica* (sinistral) on the Vøring Plateau is at 2.3 Ma. In that area there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this (Spiegler & Jansen 1989). *G. bulloides* is also found in the warmest interglacials of the last 1 Ma (Kellogg 1977). According to King (1989) the FAD of *C. grossus* is observed somewhat above the Lower/Upper Pliocene boundary. The fact that the content of *C. grossus* is considerably greater at the base of the unit than in younger sediments seems to indicate that its occurrence is not caved, but is *in situ*. Therefore, the entire zone was in all likelihood deposited in the Late Pliocene. This is also supported by the fact that *E. hannai*, which according to King (1989) also has its FAD in the Upper Pliocene, is registered only at the base of the zone.

N. pachyderma (sinistral, encrusted) indicates caved material from the M–A and M–B zones. *N. atlantica* (dextral) is probably reworked from Upper Miocene material (Spiegler & Jansen 1989). Reworked agglutinated foraminifera from the Lower Cenozoic, and benthonic and planktonic calcareous foraminifera from the Upper Cretaceous are registered in this zone and in the M–A and M–B zones. The base of the M–C zone coincides with a regional seismic reflector, representing a hiatus.

CIBICIDES TELEGDI–EPONIDES PYGMEUS–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–H.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *N. atlantica* (dextral). The base of the zone is marked by the highest occurrence of *Ehrenbergina variabilis* and *Globocassidulina subglobosa*.

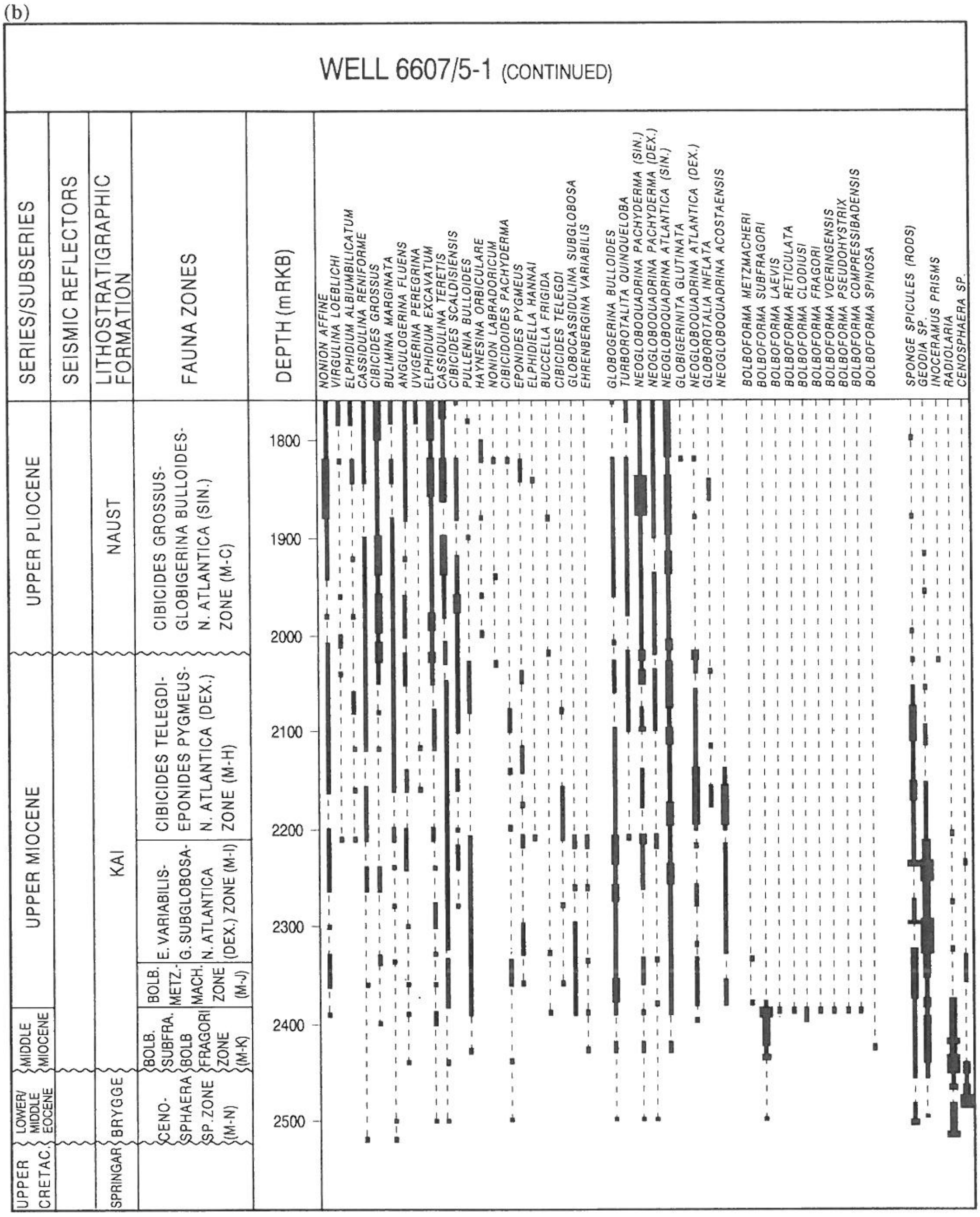


Fig. 8. (a) Range chart of the most important index fossils in the upper part of the investigated interval of well 6607/5-1. M RKB = meters below rig floor, m MSL = meters below mean sea level. (b). Range chart of the most important index fossils in the lower part of the investigated interval of well 6607/5-1.

Depth range: 2020–2211 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and probably lower part of *Melonis–Trifaria* zone of Stratlab (1988).

Assemblage: There are significantly fewer foraminifera in this interval than in the overlying zones. In addition, specimens of sponge spicules (rod-shaped and the round *Geodia* sp.) are common in this zone. Benthonic calcareous species include: *C. telegdi*, *E. pygmeus*, *C. reniforme*, *B. marginata*, *C. teretis*, *C. scaldisiensis*, *N. affine* and *Pullenia bulloides*. *C. grossus* is registered in the upper part of the zone (Fig. 8b).

Planktonic foraminifera include: *N. atlantica* (sinistral) and *N. atlantica* (dextral). *N. atlantica* (sinistral) is common in the upper part of the interval and *N. atlantica* (dextral) in the lower part. Other important species are *G. bulloides*, *N. pachyderma* (sinistral) and *N. acostaensis* (lower part). A small number of *N. pachyderma* (dextral), *T. quinqueloba* and *G. inflata* are also found.

Remarks: Most of the registered benthonic specimens are known from sediments covering almost the entire Neogene. However, *C. telegdi* and *E. pygmeus* are described from the Upper Oligocene and older deposits in Denmark and Germany (Grossheide & Trunko 1965; Hausmann 1964; Kummerle 1963, Ulleberg 1974). These species are recorded in the Upper Miocene sediments in the northern North Sea and on the Mid-Norwegian continental shelf (Eidvin & Riis 1992; Stratlab 1988), showing that these species have a time-transgressive LAD from south to north. Spiegler & Jansen (1989) describe a lower *N. atlantica* (dextral) zone from Upper Miocene sediments on the Vøring Plateau. The occurrence of *N. atlantica* (dextral) is probably *in situ* and indicates that this interval is of Late Miocene age. *N. acostaensis* is reported from deposits of Late to Middle Miocene age on the Vøring Plateau (Spiegler & Jansen 1989).

In the upper part of the interval a few specimens of *C. grossus* are recorded. These are probably caved. Other caved material is also observed.

EHRENBERGINA VARIABILIS–GLOBOCASSIDULINA SUBGLOBOSA – N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–I.

Depth range: 2211–2337 m.

Informal boundary criteria: The top of the zone is taken at the highest occurrences of *E. variabilis* and *G. subglobosa*. The base of the zone is marked by the highest occurrence of *Bolboforma metzmacheri*.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and *G. subglobosa–E. variabilis* zone of Stratlab (1988).

Assemblage: In this zone the benthonic faunas include calcareous foraminifera and sponge spicules. Sponge spicules (rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. Benthonic foraminifera include: *G. subglobosa*, *C. teretis*, *N. affine*, *A. fluens*, *P. bulloides*, *E. pygmeus* and *E. variabilis* (Fig. 8b).

Planktonic foraminifera include: *G. bulloides* (common), *N. atlantica* (sinistral; common), *N. atlantica* (dextral), *N. acostaensis*, *N. pachyderma* (sinistral; unencrusted; few) and *N. pachyderma* (dextral; few).

Remarks: Most of the benthonic foraminifera are known from almost the entire Neogene. Some of these are probably caved. *E. variabilis* is described from the Upper Oligocene to Lower Miocene of Germany (Grossheide & Trunco 1965; Spiegler 1974), from the Upper Oligocene to Lower Pliocene on the Norwegian continental shelf (Skarbø & Verdenius 1986) and from the Upper Miocene on the Mid-Norwegian continental shelf (Stratlab 1988). This species also seems to have a south to north time-transgressive appearance. *G. subglobosa* is described from the Middle to Upper Miocene of Belgium (Doppert 1980) and from the Upper Oligocene to Upper Miocene of Germany (Spiegler 1974). These forms are also described from the Upper Miocene of the northern North Sea (Eidvin & Riis 1992). *N. atlantica* (dextral) and *N. acostaensis* also indicate a Late Miocene age for this interval (Jansen & Spiegler 1989).

BOLBOFORMA METZMACHERI ZONE

Category: Informal partial range zone.

Designation: M–J.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *B. metzmacheri*. The base of the zone is marked by the highest occurrence of *B. subfragori*.

Depth range: 2337–2382 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: *B. metzmacheri* zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), Zone NSR 10 of Gradstein & Bäckström (1996), Subzone NSP 14b of King (1989) and *B. metzmacheri* zone of Stratlab (1988).

Assemblage: The greater proportion of the fossils in this sequence are sponge spicules. Considerably fewer foraminifera are registered. A small number of *B. metzmacheri* are also registered. Both calcareous benthonic foraminifera and agglutinated taxa are present, calcareous species being dominant. Important calcareous species are: *C. teretis*, *N. affine*, *P. bulloides*, *E. pygmeus* and *G. subglobosa*. The most important agglutinated species is: *Martinottiella communis*. The most important planktonic foraminifera are: *G. bulloides*, *N. atlantica* (dextral), *N. atlantica* (sinistral) and *N. acostaensis* (Fig. 8b).

Remarks: *M. communis* is known from the Middle Miocene of Belgium (Batjes 1958) and from the Middle Miocene to Lower Pliocene of The Netherlands (Doppert 1980). *B. metzmacheri* is described from deposits with an age of 9.2–7.9 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992; Müller & Spiegler 1993).

BOLBOFORMA SUBFRAGORI–BOLBOFORMA FRAGORI ZONE

Category: Informal partial range zone.

Designation: M–K.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *B. subfragori*. The base of the zone is marked by the highest consistent occurrence of *Cenosphaera* sp.

Depth range: 2382–2448 m.

Age: Middle Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: *B. fragori*/*B. subfragori* zone of Spiegler & Müller (1992) and Müller & Spiegler (1993), Subzone NSP 14a of King (1989) and *B. spiralis* zone of Stratlab (1988).

Assemblage: Sponge spicules (rod-shaped and *Geodia* sp.) and *Bolboforma* are dominant in this interval, with foraminifera being subordinate. *B. subfragori* occurs frequently throughout the sequence. *B. metzmacheri*, *B. laevis*, *B. reticulata*, *B. clodiusi*, *B. fragori*, *B. voeringensis*, *B. pseudohystrix*, *B. compressibadensis* and *B. spinosa* are recorded in the upper part of the interval. Both calcareous benthonic foraminifera and agglutinated taxa are present. Important calcareous species are: *P. bulloides*, *G. subglobosa* and *E. variabilis*. *M. communis* is the only agglutinated form recorded. The most important planktonic foraminifera are: *G. bulloides*, *N. atlantica* (sinistral) and *N. atlantica* (dextral) (Fig. 8b).

Remarks: The known stratigraphic ranges of the important benthonic and planktonic foraminifera registered in this interval are discussed above under the descriptions of Zones M–I and M–J. A *B. fragori*/*B. subfragori* zone is described from deposits with an age of slightly less than 12–9.6 Ma from the North Atlantic and the Vøring Plateau (Spiegler & Müller 1992 and Müller & Spiegler 1993).

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 2448–2520 m.

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna of this sequence is almost completely dominated by radiolarians, mostly *Cenosphaera* sp. In addition, some sponge spicules and a few foraminifera are recorded (Fig. 8b).

Remarks: *A Cenosphaera* sp. acme is known from the Lower to Middle Eocene of the North Sea (King 1989). The foraminifera found in this interval are probably caved. The deposits immediately below this interval are assigned to an age of Late to Middle Campanian based on dinoflagellates (Robert Williams, pers. comm., 1991).

WELL 6607/5-2 (66°41′N, 7°21′E)

CIBICIDES GROSSUS–GLOBIGERINA BULLOIDES–NEOGLOBOQUADRINA ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–C.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (2290 m). The base of the zone is marked by the lowest abundant occurrence of *Cenosphaera* sp.

Depth range: 2290 (uppermost investigated sample) – 2320 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. *E. excavatum* and *C. grossus* occur frequently throughout the zone. Other important species are: *N. affine*, *B. marginata*, *C. teretis*, *Elphidium subarcticum* and *C. scaldisiensis* (Fig. 9).

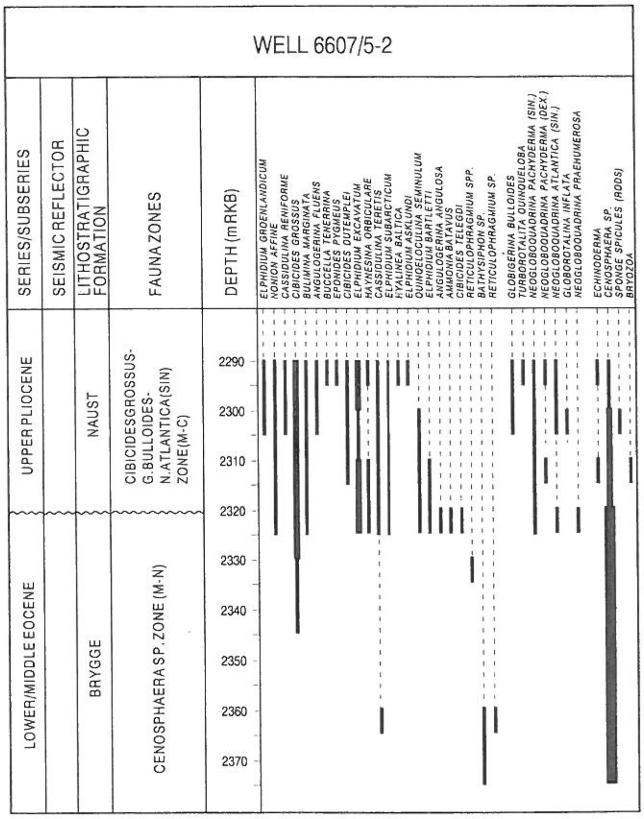


Fig. 9. Range chart of the most important index fossils in the investigated interval of well 6607/5-2. M RKB = meters below rig floor, m MSL = meters below mean sea level.

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. pachyderma* (sinistral, unencrusted) and *N. atlantica* (sinistral) are dominant. Other important species are: *G. bulloides*, *N. pachyderma* (dextral) and *G. inflata*.

Remarks: The occurrence of *C. grossus*, *N. atlantica* (sinistral) and *G. bulloides* indicates that this interval is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989).

The common occurrence of the radiolarian *Cenosphaera* sp. indicates redeposition of Lower to Middle Eocene sediments. The benthonic calcareous foraminifera *E. pygmeus* and *C. telegdi* are reworked Oligocene–Miocene taxa. The base of Zone M–C coincides with a regional seismic reflector which represents a depositional hiatus.

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest abundant occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 2320–2370 m (lowest sample analyzed).

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna in this interval is dominated by the radiolarian *Cenosphaera* sp. Some sponge spicules and foraminifera are also recorded (Fig. 9).

Remarks: *A Cenosphaera* sp. acme is known from the Lower to Middle Eocene of the North Sea (King 1989). This zone is coeval with the M–N zone in well 6607/5-1. Most of the foraminifera are found in the uppermost sample, and are caved from the above interval.

WELL 6506/12-4 (65°12′N, 6°43′E)

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL)–*NONION LABRADORICUM* ZONE

Category: Informal partial range zone.

Designation: M–A.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (370 m) and probably to near the sea floor. The base of the zone is marked by the highest occurrence of *C. grossus* and the highest consistent occurrence of *N. atlantica* (sinistral).

Depth range: 370 (uppermost investigated sample) – 660 m.

Age: Pleistocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzone NSB 16x of King (1989), Zone NSR 13 of Gradstein & Bäckström (1996) and *N. pachyderma* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna consisting mainly of calcareous foraminifera, of which *E. excavatum* is the most common. *C. reniforme* and *B. marginata* are also common. Other characteristic forms are: *N. labradoricum*, *V. loeblichi*, *B. tenerrima*, *C. teretis*, *C. scaldisiensis*, *N. affine* and *U. peregrina* (Fig. 10a).

Planktonic foraminifera are also quite common, but less frequent than the calcareous benthonic taxa. *N. pachyderma* (both encrusted and unencrusted varieties of the sinistrally coiled individuals) is dominant. Other important species are: *N. pachyderma* (dextral), *G. bulloides* and *T. quinqueloba*.

Remarks: The occurrence of *N. pachyderma* (sinistral, encrusted) and *N. labradoricum* indicates that this zone is of Pleistocene age (King 1989; Spiegler & Jansen 1989).

The base of this interval coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

CIBICIDES GROSSUS–GLOBIGERINA BULLOIDES–N. ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–C.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *C. grossus* and the highest consistent occurrence of *N. atlantica* (sinistral). The base of the zone is marked by the highest occurrence of *E. hannai*.

Depth range: 660–1040 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of mainly calcareous foraminifera. *E. excavatum*, *B. marginata*, *C. teretis* and *C. grossus* all occur frequently throughout. Other important species are: *N. affine*, *C. lobatulus*, *E. albiumbilicatum*, *C. pachyderma* and *B. tenerrima* (Fig. 10a).

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (sinistral), *G. bulloides* and *N. pachyderma* (sinistral; both encrusted and unencrusted varieties) are dominant. The encrusted variety of *N. pachyderma* (sinistral) is common in the upper part of the interval. The unencrusted variety is common in the lower part. Other species are: *N. pachyderma* (dextral) and *N. atlantica* (dextral).

Remarks: The occurrence of *C. grossus*, *N. atlantica* (sinistral) and *G. bulloides* indicates that this interval is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989). The youngest part of the Late Pliocene is not therefore recorded in well 6506/12-4. This is supported by the fact that Zone M–B is not present.

N. atlantica (dextral) is recorded once in the Upper Pliocene (2.3–2.0 Ma) and once in the Upper Miocene on the Vøring Plateau (Spiegler & Jansen 1989). This indicates either that *N. atlantica* has a somewhat different range in this area than on the Vøring Plateau, or that the recorded specimens are reworked from Upper Miocene deposits. *N. pachyderma* (sinistral, encrusted) is caved from Zone M–A.

CIBICIDES GROSSUS–ELPHIDIELLA HANNAI–GLOBIGERINA BULLOIDES–N. ATLANTICA (SINISTRAL) ZONE

Category: Informal assemblage zone.

Designation: M–D.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *E. hannai*. The base of the zone is marked by highest consistent occurrence of *N. atlantica* (dextral).

Depth range: 1040–1480 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: The assemblage in this zone is very similar to that in Zone M–C, the main difference being the presence of *E. hannai* (Figs. 10a, b).

Remarks: The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinistral) indicates that this zone is of Late Pliocene age (King 1989; Spiegler & Jansen 1989). The occurrence of *E. hannai* indicates that the sediments are of a more shallow marine origin than in Zone M–C (Feyling-Hanssen 1986; Skarbø & Verdenius 1986).

In this zone and in the M–A and M–C zones reworked agglutinated foraminifera are recorded from the Lower Cenozoic, benthonic and planktonic calcareous foraminifera from the Upper Cretaceous and *Inoceramus* prisms from the Upper Cretaceous. The base of the M–D zone coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

NONION AFFINE–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–G.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *N. atlantica* (dextral). The base of the zone is marked by the highest occurrence of *C. telegdi*.

Depth range: 1480–1660 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and probably Melonis–Trifarina zone of Stratlab (1988).

Assemblage: This zone contains a medium-rich benthonic fauna of mainly calcareous foraminifera. Sponge spicules (rod-shaped and *Geodia* sp.) are also recorded in this zone. The benthonic calcareous foraminifera include *N. affine* and *C. teretis*, which are the most common species, and which occur throughout the zone. Other characteristic species are: *C. lobatulus*, *I. islandica*, *B. marginata* and *A. fluens*.

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (sinistral), *G. bulloides*, *N. atlantica* (dextral) and *T. quinqueloba are dominant*. Other species are: *N. pachyderma* (sinistral, unencrusted), *N. pachyderma* (dextral), *G. inflata* and *G. puncticulata* (Fig. 10b).

Remarks: The consistent appearance of *N. atlantica* (dextral) indicates that these specimens are *in situ*, and that the zone represents the lower *N. atlantica* (dextral) zone seen on the Vøring Plateau. Spiegler & Jansen (1989) have described the lower *N. atlantica* (dextral) zone from Upper Miocene sediments in that area. This is the uppermost zone of the Kai Formation, and was not encountered in well 6607/5-1.

CIBICIDES TELEGDI–EPONIDES PYGMEUS–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–H.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *C. telegdi*. The base of the zone is marked by the highest occurrence of *E. variabilis* and *G. subglobosa*.

Depth range: 1660–1770 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989) and probably the lower part of Melonis–Trifarina zone of Stratlab (1988).

Assemblage: This interval contains a medium-rich benthonic fauna of calcareous foraminifera. Sponge spicules (rod-shaped and *Geodia* sp.) are also recorded in this zone. The benthonic calcareous foraminifera include: *N. affine* and *C. teretis*, which are the most common species.

Other important species are: *C. telegdi*, *E. pygmeus*, *C. reniforme*, *A. fluens*, *B. marginata* and *Epistominella* sp. (Fig. 10b).

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (dextral), *N. atlantica* (sinistral), *G. bulloides* and *T. quinqueloba* are dominant. Other species are: *N. acostaensis*, *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral).

Remarks: This zone is coeval with the M–H zone in well 6607/5-1, and both intervals are of Late Miocene age.

EHRENBERGINA VARIABILIS–GLOBOCASSIDULINA SUBGLOBOSA–N. ATLANTICA (DEXTRAL) ZONE

Category: Informal partial range zone.

Designation: M–I.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *E. variabilis* and *G. subglobosa*. The base of the zone is marked by the highest occurrence of Diatom sp. 3.

Depth range: 1770–1920 m.

Age: Late Miocene.

Lithostratigraphic formation: Kai Formation.

Equivalent zones: Lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989), and *G. subglobosa– E. variabilis* zone of Stratlab (1988).

Assemblage: The benthonic fauna within this interval includes calcareous foraminifera and sponge spicules. Sponge spicules (rod-shaped and *Geodia* sp.) are significantly more common than foraminifera. Benthonic calcareous foraminifera include: *N. affine* and *C. teretis*, which are the most common species and which occur throughout the zone. Other important species are: *G. subglobosa*, *E. variabilis*, *C. telegdi*, *E. pygmeus*, *A. fluens* and *B. marginata* (Fig. 10b).

Planktonic foraminifera are less frequent than calcareous benthonic taxa. *N. atlantica* (dextral), *N. atlantica* (sinistral), *G. bulloides* and *T. quinqueloba* are dominant. Other species are: *N. acostaensis*, *N. pachyderma* (sinistral, unencrusted) and *N. pachyderma* (dextral).

Remarks: This zone is coeval with the M–I zone in well 6607/5-1 and both intervals are of Late Miocene age. The base of this interval coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

DIATOM SP. 3 ZONE

Category: Informal partial range zone.

Designation: M–L.

Depth range: 1920–1960 m.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of Diatom sp. 3. The base of the zone is marked by the highest consistent occurrence of *Cenosphaera* sp.

Age: Late Oligocene to Early Miocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Subzone NSP 9c of King (1989) and Diatom sp. 3 zone of Stratlab (1988).

Assemblage: Most fossils in this interval are radiolarian. Considerably fewer diatoms, sponge spicules and benthonic and planktonic foraminifera are recorded. Some of the diatoms are Diatom sp. 3 (King 1983) (Fig. 10b).

Remarks: King (1989) employs Diatom sp. 3 as the nominate taxon for the Late Oligocene–Early Miocene Subzone NSP 9c of the North Sea. Most of the foraminifers found in this interval are probably caved.

(a)

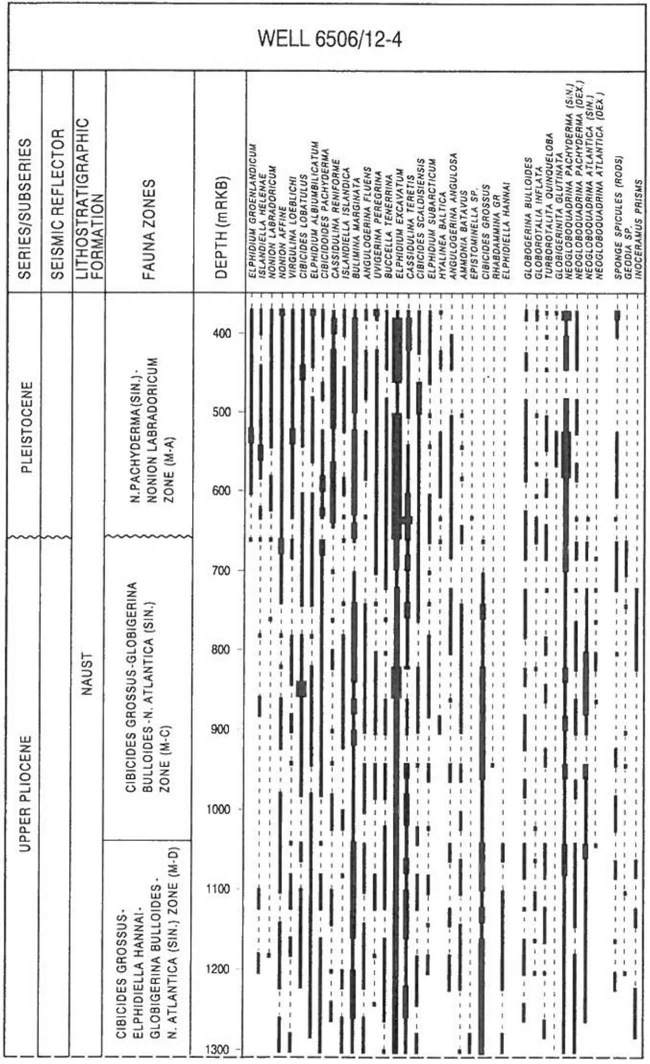


Fig. 10(a). (Legend overleaf).

(b)

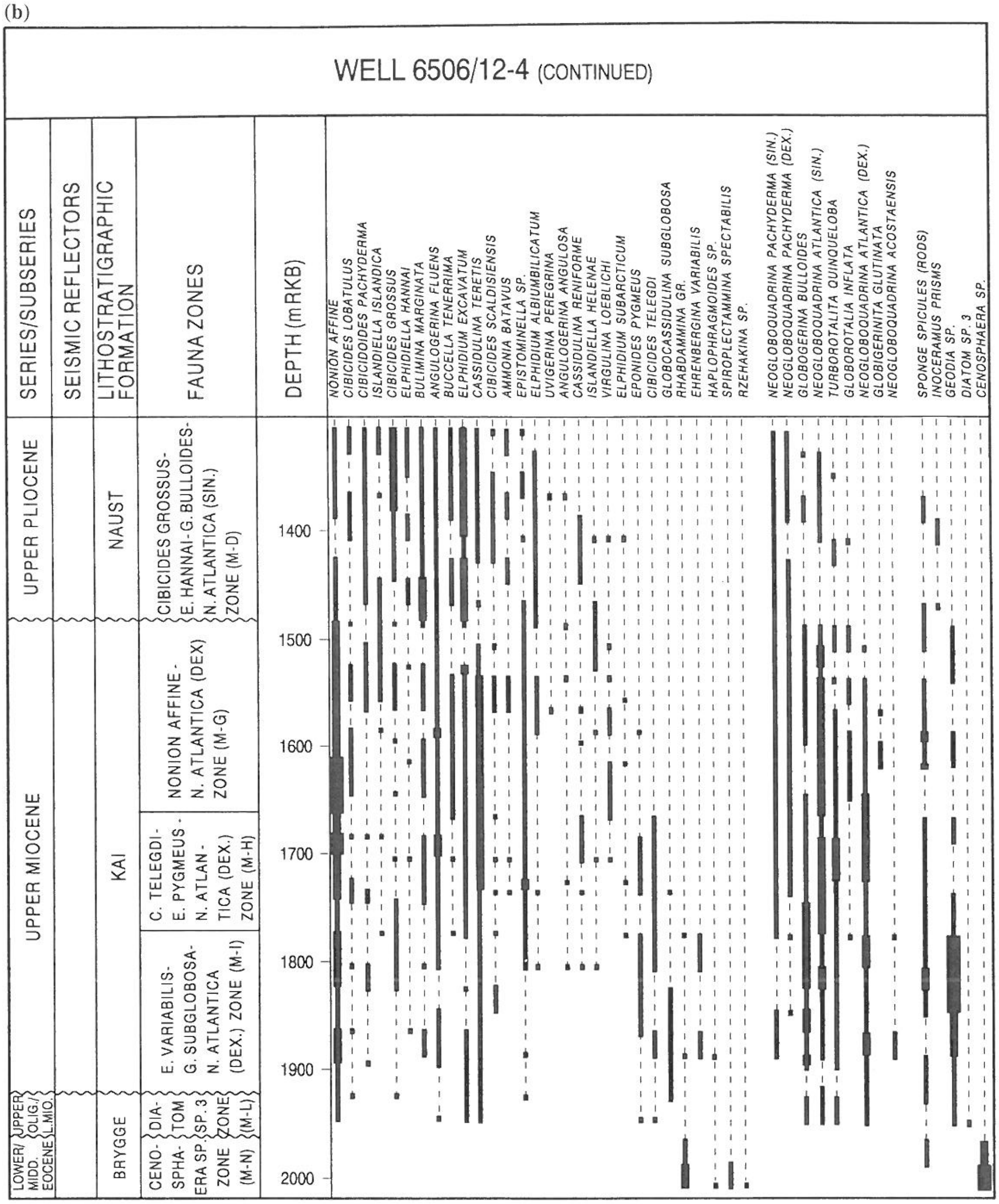


Fig. 10. (a) Range chart of the most important index fossils in the upper part of the investigated interval of well 6506/12-4. M RKB = meters below rig floor, m MSL = meters below mean sea level. (b). Range chart of the most important index fossils in the lower part of the investigated interval of well 6506/12-4.

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 1960–2000 m (lowest sample analyzed).

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna in this interval is dominated by the radiolarian *Cenosphaera* sp. In addition, agglutinated foraminifera and sponge spicules are recorded. The agglutinated foraminifera include the *Rhabdammina* group, which is the most common. Other species are *Spiroplectammina spectabilis*, *Haplophragmoides* sp. and *Rzehakina* sp. (Fig. 10b).

Remarks: *S. spectabilis* and a *Cenosphaera* sp. acme is known from the Lower to Middle Eocene of the North Sea (King 1989). This zone is coeval with the M–N zones in the wells 6607/5-1 and /5-2.

WELL 6610/7-2 (66°27′N, 10°10′E)

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) – *NONION LABRADORICUM* ZONE

Category: Informal partial range zone.

Designation: M–A.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (330 m) and probably to near the sea floor. The base of the zone is taken at the highest occurrence of *E. hannai*, *N. atlantica* (sinistral) and *G. bulloides* and the highest consistent occurrence of *C. grossus*.

Depth range: 330 (uppermost investigated sample) – 410 m.

Age: Pleistocene.

Lithostratigraphic formation: Naust formation.

Equivalent zones: Subzone NSB 16x of King (1989), Zone NSR 13 of Gradstein & Bäckström (1996) and the *N. pachyderma* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum*, *C. lobatulus*, *C. reniforme* and *B. marginata* occur most frequently. Other important species are: *N. labradoricum*, *Islandiella islandica*, *Islandiella helenae*, *C. teretis*, *N. affine* and *B. tenerrima* (Fig. 11).

The planktonic foraminifera are considerably less frequent than benthonic taxa and include: *N. pachyderma* (both encrusted and unencrusted varieties of sinistrally coiled individuals), *N. pachyderma* (dextral) and *T. quinqueloba*.

Remarks: The occurrence of *N. pachyderma* (sinistral, encrusted) and *N. labradoricum* indicates that this zone is of Pleistocene age (King 1989; Spiegler & Jansen 1989).

CIBICIDES GROSSUS–ELPHIDIELLA HANNAI–GLOBIGERINA BULLOIDES–N. ATLANTICA (SINISTRAL) ZONE

Category: Informal partial range zone.

Designation: M–D.

Informal boundary criteria: The top of the zone is taken at the highest occurrence of *E. hannai*, *N. atlantica* (sinistral) and *G. bulloides* and the highest consistent occurrence of *C. grossus*. The base of the zone is marked by the highest consistent occurrence of *Coscinodiscus* sp. 1.

Depth range: 410–1002 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This zone contains a rich benthonic fauna of calcareous foraminifera. *E. excavatum*, *C. teretis*, *C. lobatulus*, *E. albiumbilicatum*, *C. grossus* and *E. hannai* all occur frequently throughout (Fig. 11).

Planktonic foraminifera are less frequent than benthonic taxa. *G. bulloides* and *N. atlantica* (sinistral) are the most common species. *N. pachyderma* (sinistral) and *N. pachyderma* (dextral) are recorded in the upper part of the interval.

Remarks: In addition to analyses of drill cuttings, the investigation of this zone is based on analyses of seven sidewall cores from the interval between 712 m and 1002 m.

The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinistral) indicates that this interval is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989). The youngest part of the Late Pliocene is therefore not recorded in well 6610/7-2. The zone is coeval with the M–C and M–D zones in wells 6506/12-4, 6607/5-1 and /5-2. The base of Zone M–D coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

COSCINODISCUS SP. 1 ZONE

Category: Informal partial range zone.

Designation: M–O.

Depth range: 1002–1100 m (lowest sample analyzed).

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Coscinodiscus* sp. 1. The base of the zone is undefined.

Age: Late Paleocene to Early Eocene.

Lithostratigraphic formation: Tare Formation.

Equivalent zones: Zone NSP 4 of King (1989), Zone NSR 3 of Gradstein & Bäckström (1996) and *Coscinodiscus* sp. 1 zone of Stratlab (1988).

Assemblage: The greater proportion of the fossils from this interval are diatoms. Sponge spicules and radiolaria are also recorded. The diatoms include *Coscinodiscus* sp. 1 (common), *Triceratium* sp. 1 and *Coscinodiscus* sp. 2 (Fig. 11).

Remarks: King (1989) employs *Coscinodiscus* sp. 1 as the nominate taxon for the Upper Paleocene – Lower Eocene Zone NSP 4 of the North Sea.

WELL 6610/7-1 (66°17′N, 10°16′E)

CIBICIDES GROSSUS–ELPHIDIELLA HANNAI ZONE

Category: Informal partial range zone.

Designation: M–E.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (710 m). The base of the zone is marked by the lowest occurrence of *C. grossus*.

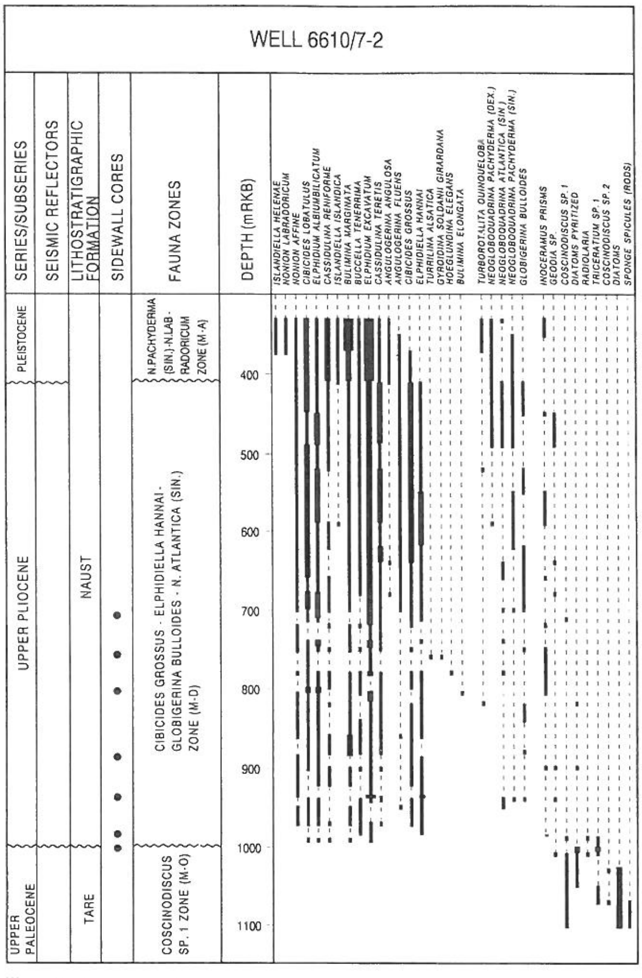


Fig. 11. Range chart of the most important index fossils in the investigated interval of well 6610/7-2. M RKB = meters below rig floor, m MSL = meters below mean sea level.

Depth range: 710 (uppermost investigated sample) – 830 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), *C. grossa* zone of Stratlab (1988) and *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This zone contains a medium-rich benthonic fauna of calcareous foraminifers. *B. marginata*, *C. teretis* and *E. excavatum* occur most frequently. Other important species are: *C. grossus*, *E. hannai*, *N. affine*, *C. lobatulus*, *E. albiubilicatum*, *C. reniforme* and *A. fluens*. *G. bulloides*, *N. atlantica* (sinistral) and *T. quinqueloba* are sporadic planktonic representatives (Fig. 12).

Remarks: The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinistral) indicates that this zone is of Late Pliocene age, but older than 2.3 Ma (King 1989; Spiegler & Jansen 1989). This zone is coeval with the M–C and M–D zones in wells 6607/5-1, 6607/5-2, 6506/12-4 and 6610/7-2.

EPHIDIELLA HANNAI ZONE

Category: Informal partial range zone.

Designation: M–F.

Informal boundary criteria: The top of the zone is taken at the lowest occurrence of *C. grossus*. The base of the zone is marked by the lowest occurrence of *E. hannai*.

Depth range: 830–890 m.

Age: Late Pliocene.

Lithostratigraphic formation: Naust Formation.

Equivalent zones: Subzones NSB 15a and b of King (1989), the *C. grossa* zone of Stratlab (1988) and the *N. atlantica* (sinistral) zone of Spiegler & Jansen (1989).

Assemblage: This interval contains a moderately rich benthonic fauna of calcareous foraminifers; these are less frequent than in Zone M–E. No planktonic foraminifera have been recorded. *E. excavatum* is dominant. Other important species include: *E. hannai*, *B. marginata*, *B. tenerrima*, *N. affine*, *C. lobatulus*, *E. albiumbilicatum* and *H. orbiculare* (Fig. 12).

Remarks: The presence of *E. hannai* indicates that this interval is of Late Pliocene age (King 1989). This zone is coeval with the M–D zones in wells 6506/12-4 and 6610/7-2. The base of Zone M–F coincides with a regional seismic reflector which is interpreted to represent a depositional hiatus.

UNZONED INTERVAL

Depth range: 890–970 m.

Age: Early Oligocene.

Lithostratigraphic formation: Frøyrygg Formation (informal) or Molo Formation (informal).

Assemblage: A few calcareous benthonic foraminifera are registered in the upper part of this interval, and a few radiolaria and sponge spicules are recorded in the lower part. The palynoflora has also been investigated in this interval. The sample at 900 m is dominated by spores and pollen thought to be of Griesbachian–Late Permian age together with a small number of dinoflagellates. Otherwise, poorly preserved and impoverished dinoflagellate associations have been observed down to 960 m. The sample at 920 m contains *Alisocysta margarita*, while that at 960 m contains *Deflandrea oebisfeldensis*.

Remarks: The calcareous benthonics recorded from this interval are Upper Pliocene/Pleistocene forms and are probably caved. The radiolaria and sponge spicules are most likely reworked. The dinoflagellate *A. margarita* is thought to be reworked from the Paleocene while *D. oebisfeldensis* is reworked from the Lower Eocene–

Paleocene. Other recorded species range from Pliocene to Eocene.

The sediment in this interval is the same coarse, rust-stained sand as found in the upper part of Zone M–M in well 6610/3-1. Zone M–M has been dated to Early Oligocene, and correlation to seismic data indicates that these intervals are the same.

CENOSPHAERA SP. ZONE

Category: Informal partial range zone.

Designation: M–N.

Informal boundary criteria: The top of the zone is taken at the highest consistent occurrence of *Cenosphaera* sp. The base of the zone is undefined.

Depth range: 970–1090 m (lowest sample analyzed).

Age: Early to Middle Eocene.

Lithostratigraphic formation: Brygge Formation.

Equivalent zones: Zone NSP 6 of King (1989).

Assemblage: The fauna in this interval is dominated by the radiolarian *Cenosphaera* sp. Some agglutinated foraminifera and sponge spicules are also recorded. The agglutinated foraminifera include *S. spectabilis*, which are the most common. Other species are *Reticulophragmium* sp. *Trochammina* sp. and the *Rhabdammina* group (Fig. 12).

Remarks: *S. spectabilis* and a *Cenosharera* sp. acme are known from the Lower to Middle Eocene of the North Sea (King 1989). This zone is coeval with the M–N zones in wells 6607/5-1, 6607/5-2 and 6506/12-4.

WELL 6610/3-1 (66°55′N, 10°54′E)

GYROIDINA SOLDANII GIRARDANA–BOLIVINA CF. *ANTIQUA* ZONE

Category: Informal assemblage zone.

Designation: M–M.

Informal boundary criteria: The top of the zone extends above the uppermost investigated sample (460 m). The base of the zone is undefined.

Depth range: 460–555 m.

Age: Early Oligocene.

Lithostratigraphic formation: Frøyrygg Formation (informal) or Molo Formation (informal).

Equivalent zones: Zone NSB 7 of King (1989) and Zone NSR 7A or NSR 7B of Gradstein & Bäckström (1996).

Assemblage: The biostratigraphic analyses of this well are based on five sidewall cores only. The three uppermost samples contain only a few calcareous benthonic foraminifera. The two lowermost samples contain a rich calcareous benthonic fauna. *Gyroidina soldanii girardana*, *P. bulloides*, *C. telegdi*, *Nodosaria* sp. and *Cibicides dutemplei* appear throughout the sequence. *Cibicides aknerianus*, *Alabamina tangentialis*, *G. subglobosa*, *Hoeglundina elegans*, *Alabamina wolterstorfi*, *Stilostomella adolphina*, *Guttulina problema*, *Cibicides dobergensis*, *Turrilina alsatica* and *Bolivina* cf. *antiqua* are all encountered in the two lowermost samples (Fig. 13).

The palynoflora has also been investigated from this interval. One feature of the assemblages is the high frequency and diversity within the genus *Phthanoperidinium*. In addition, there are large numbers of *Cribroperidinium* (reticulate forms) and an abundance of *Areosphaeridium arcuatum* at 555 m. *Areosphaeridium diktyoplokus* is recorded in variable numbers throughout the interval.

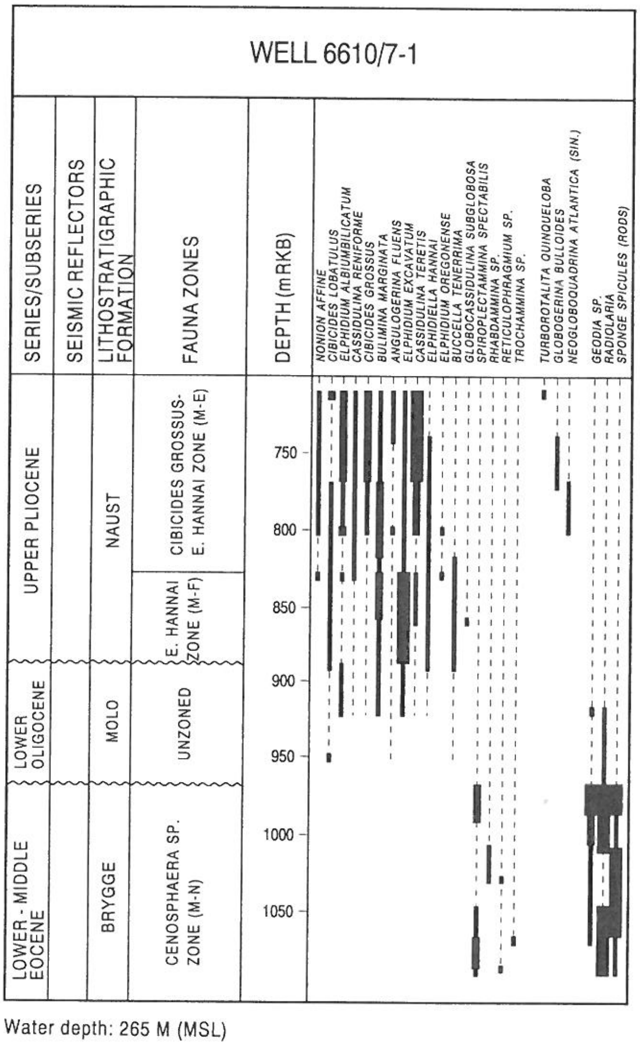


Fig. 12. Range chart of the most important index fossils in the investigated interval of well 6610/7-1. M RKB = meters below rig floor. m MSL = meters below mean sea level.

Remarks: The sediment in the three uppermost samples in this interval comprises the same coarse, rust-stained sand as encountered in the 'unzoned' interval in well 6610/7-1. The two lowermost samples contain a grey, unoxidized, mica-rich sand.

The foraminfera found in this interval are all described from the Lower Oligocene to Upper Miocene deposits in the North Sea area (Batjes 1958; Christensen & Ulleberg 1974; Ulleberg 1985; Nuglish & Spiegler 1974; King 1989). *Bolivina* cf. *antiqua* is restricted to the Upper Oligocene to lowermost Miocene sediments of the North Sea (King 1989).

Strontium-isotope analyses of tests in the sample at 525 m give an $^{87}Sr/^{86}Sr$ ratio of 0.707781 ± 11. The sample at 555 m gives an $^{87}Sr/^{86}Sr$ ratio of 0.707720 ± 9. These ratios indicate respective ages of about 35.9 and 39.8 Ma according to DePaolo & Ingram (1985), Hess et al. (1986), Koepnick et al. (1985), Palmer & Elderfield (1985) and Rundberg (pers. comm. 1995). The lowermost sample is possibly contaminated, so the uppermost analysis is probably the most reliable. The presence of the foraminifera *Bolivina* cf. *antiqua* indicates a Late Oligocene age for this unit, but since correlation of benthonic foraminifera over long distances is not always reliable, the Sr-isotope age of 35.9 Ma (Early Oligocene) is preferred.

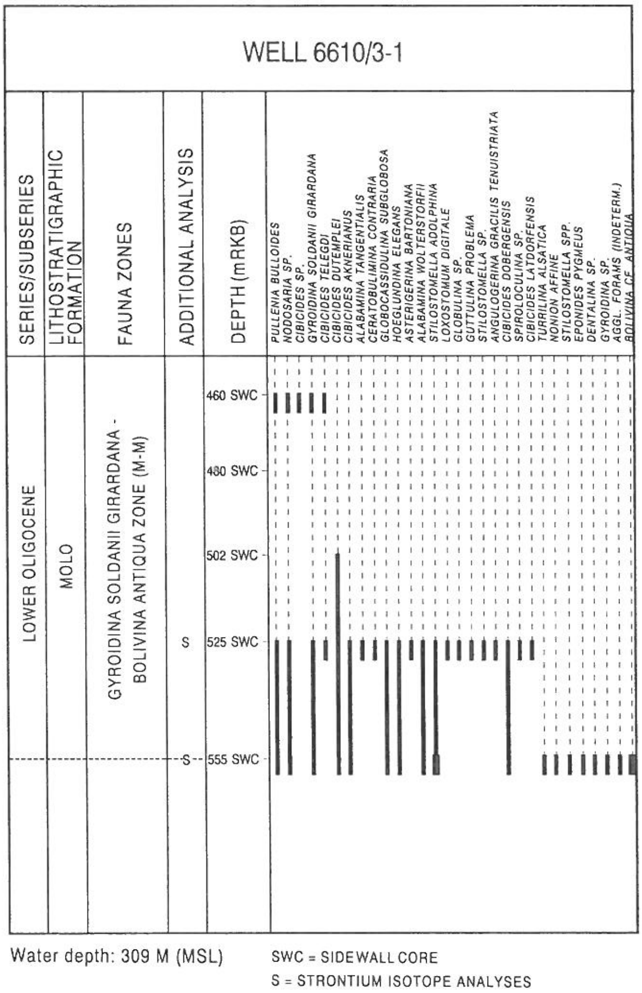


Fig. 13. Range chart of the most important index fossils in the investigated interval of well 6610/3-1. M RKB = meters below rig floor, m MSL = meters below mean sea level.

One major characteristic of the samples analyzed for palynology between 460 and 555 m is the variety of reworking present, which is derived from all levels between the Jurassic and Upper Eocene. However, based on overall assemblage composition an Early Eocene age may be assigned to most of the samples. The dinoflagellate assemblage observed in the sample at 555 m which includes abundant *A. arcuatum* suggests an age close to the Eocene/Oligocene boundary equivalent to zone O1 as illustrated in Mudge & Bujak (1994, Fig. 3). The frequency of *A. diktyoplokus*, which has a LAD at the top of the Eocene, is highly variable (in some cases the abundance levels are more typical of the Middle Eocene). In this case a Late Eocene age equivalent to Zone E8b (Bujak & Mudge 1994) is possible, though questionable due to the degree of reworking of associated Eocene palynofloras. An Early Oligocene age is also in agreement with the micropaleontological data.

Paleoenvironments

Pleistocene to Upper Pliocene

A high content of glacigenic material and polar benthonic foraminifera such as *E. excavatum*, *C. reniforme* and several forms of the genus *Elphidium* indicate cold water conditions during most of the Late Pliocene and Pleistocene. In addition, the Pleistocene sections contain several more polar forms of the genus *Islandiella*, while containing several boreal forms such as: *U. peregrina*, *A. angulosa* and *H. balthica*. This reflects the larger variation between the glacial and the interglacial periods that existed during the Pleistocene, compared with the variation that existed during Late Pliocene time, described from ODP drillings in the Norwegian Sea (Jansen & Sjøholm 1991; Berger & Jansen 1994).

In wells 6607/5-1 and /5-2, Upper Pliocene and Pleistocene deposits correspond to Fauna Zones M–A, M–C and M–D (well 6607/5-2 contains only Zone M–C). These sections are rich in planktonic foraminifera, and a large proportion of planktonic foraminifera in coastal areas indicates open marine and fairly deep water conditions. A large content of *N. affine* also indicates fairly deep water (Mackensen et al. 1985). These units were probably deposited in an outer shelf environment.

In well 6506/12-4 the Upper Pliocene and Pleistocene correspond to Fauna Zones M–A, M–C and M–D. Zone M–A has a moderately rich planktonic foraminifera fauna. Zone M–C contains a smaller number,

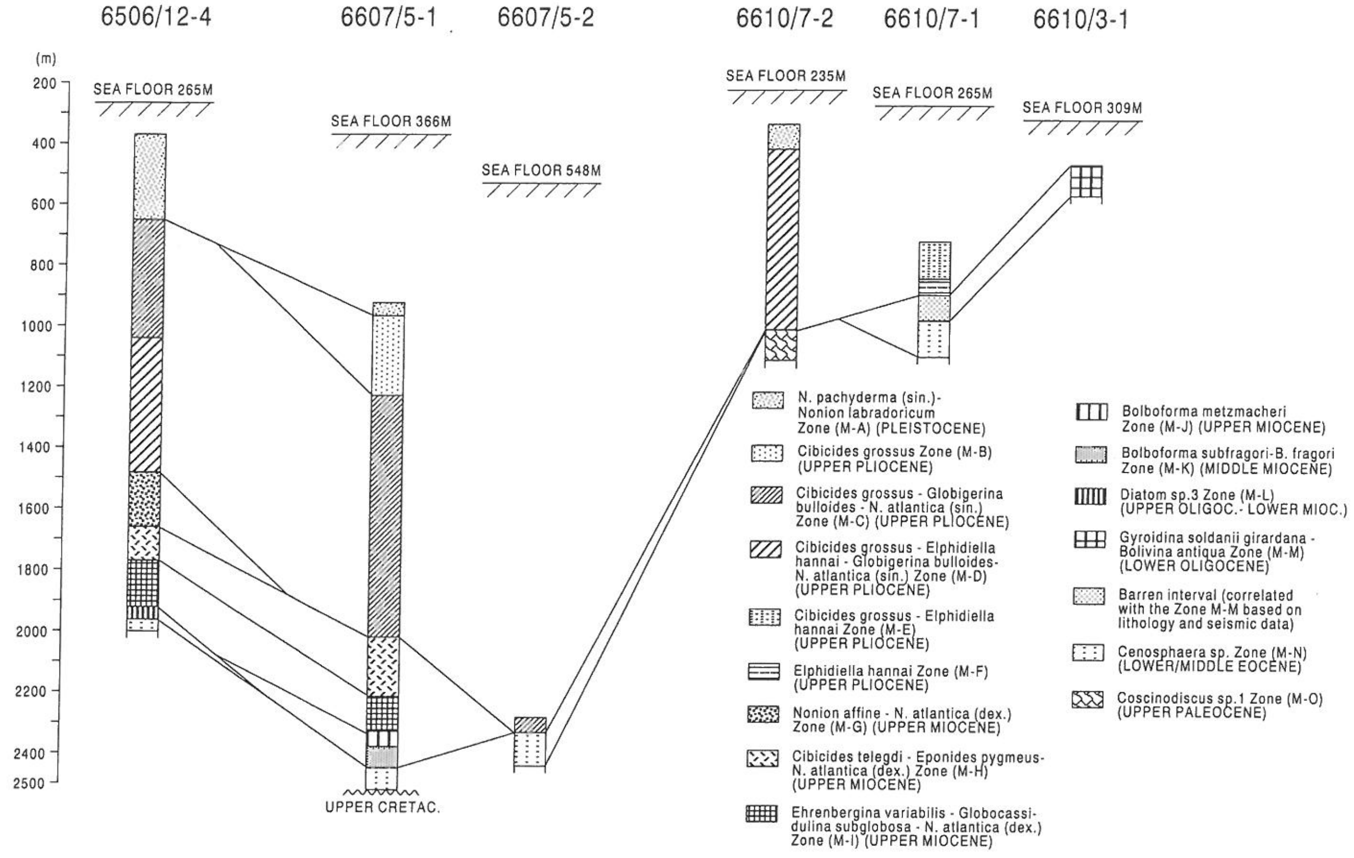


Fig. 14. Correlation of the faunal zones between the wells studied. Vertical axis is meters below rig floor.

while in Zone M–D there are few planktonic foraminifera. In Zone M–A there is a consistent occurrence of the deep-water form *N. affine*. This taxon decreases in numbers in Zone M–C, and in Zone M–D *N. affine* occurs only sporadically. In Zone M–D there is also a consistent occurrence of the shallow-water indicator *E. hannai* (Feyling-Hanssen 1986; Skarbø & Verdenius 1986). This indicates that Zone M–A was deposited in an outer shelf environment, Zone M–C in an outer to middle shelf environment and Zone M–D was probably deposited in a middle shelf environment.

In well 6610/7-2, the Upper Pliocene and Pleistocene correspond to Zones M–A and M–D. In Zone M–A there is a rare but consistent occurrence of planktonic foraminifera. This is also the case for the upper part of Zone M–D, but in the lower part of this zone there is only a sporadical occurrence. *N. affine* occurs rarely but consistently in Zone M–A and in upper part of Zone M–D. In the lower part of Zone M–D, this form occurs more sporadically. The shallow water dwelling *E. hannai* occurs consistently through Zone M–D. In this well these observations indicate that Zone M–A and the upper part of Zone M–D were deposited in a middle shelf environment, and the lower part of Zone M–D in a middle to inner shelf environment.

In well 6610/7-1 only the lower part of the Upper Pliocene is investigated, corresponding to Zones M–E and M–F. In Zone M–E there is only a sporadical occurrence of planktonic foraminifera. In Zone M–F no planktonic species are registered. There is a rare occurrence of *N. affine* in Zone M–E. *E. hannai* occurs consistently throughout both zones. This indicates that Zone M–E was deposited in an inner to middle shelf environment, and Zone M–F in an inner shelf environment.

Upper to Middle Miocene

Upper to Middle Miocene deposits (Zones M–G to M–K) are found in wells 6607/5-1 and 6506/12-4. Zone M–G is registered in well 6506/12-4 only. This zone contains a rich planktonic foraminifer fauna. Few polar and shallow-water forms have been registered, but the deep-water dwelling form *N. affine* is common throughout the zone. Zone M–G was probably deposited in an outer shelf environment.

Zones M-H and M-I are registered in both wells 6607/5-1 and 6506/12-4. Common occurrence of planktonic foraminifera, the consistent occurrence of *N.*

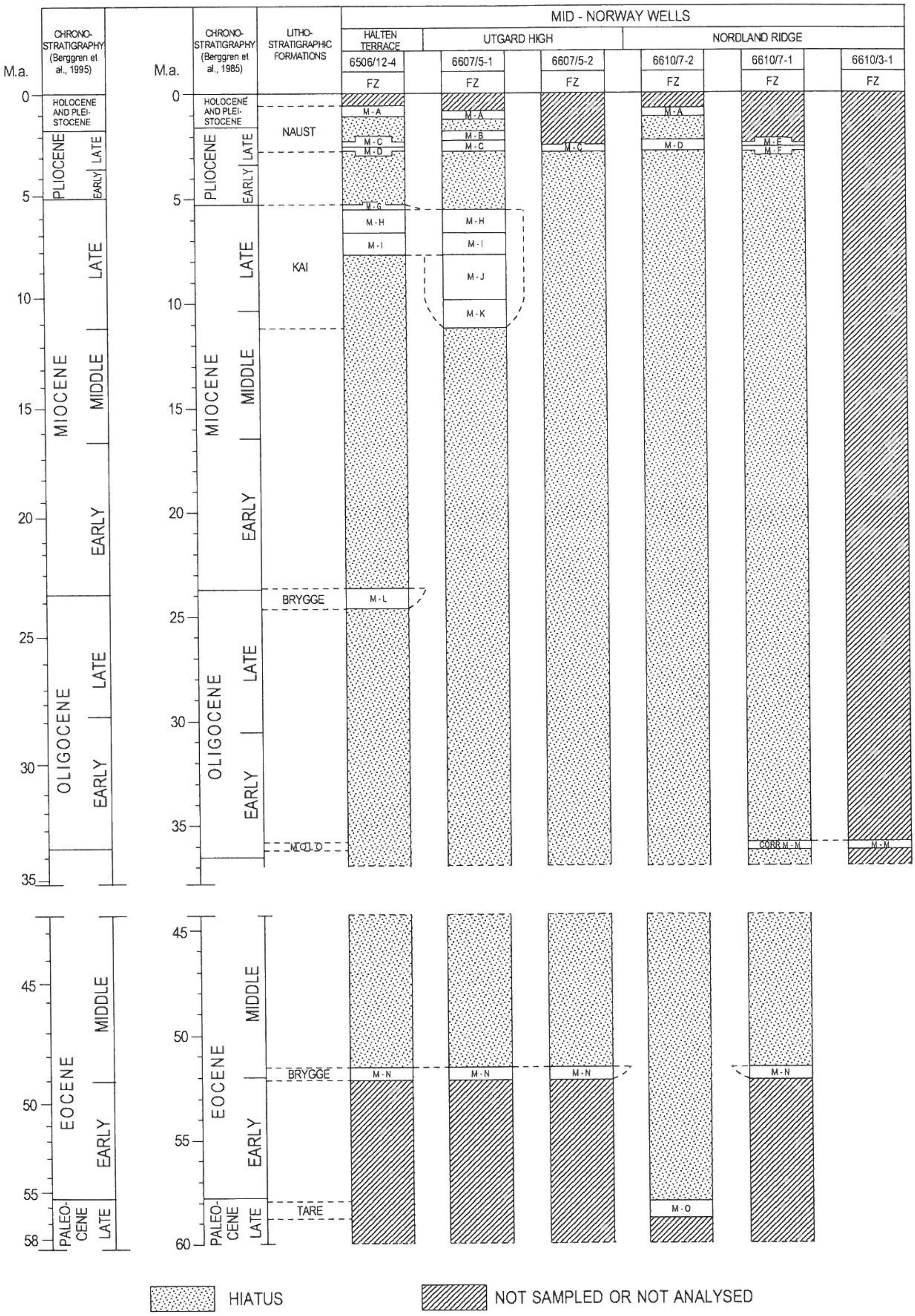


Fig. 15. Correlation of the faunal zones between the well studied. Vertical axis is Ma. Note that the ages of the Eocene and Paleocene fauna zones are less accurate than the younger fauna zones. Time scales of Berggren et al. (1985 and 1995) are presented. FZ = fauna zones.

affine and the occurrence of *P. bulloides* indicate deposition in an outer shelf environment (Mackensen et al., 1985).

Zones M-J and M-K are only registered in well 6607/5-1. Zone M-J represents the lowermost part of the Upper Miocene, and Zone M-K represents the uppermost part of the Middle Miocene. A large proportion of the microfossils in these zones are planktonic organisms (*Bolboforma* and planktonic foraminifera), indicating deep water. Registration of the benthonic forms *P. bulloides* and *M. communis* also indicate fairly deep water (Mackensen et al., 1985; Skarbø & Verdenius, 1986). Zones M-J and M-K were probably deposited in an outer shelf environment.

Base Lower Miocene to Upper Oligocene

Base Lower Miocene to Upper Oligocene deposits (Zone M–L) are only registered in well 6506/12-4. A large part of the microfossils in this section are planktonic organisms. Both radiolaria and diatoms are common, which indicates deposition in an outer to middle shelf environment.

Lower Oligocene

Zone M–M is registered in well 6610/3-1, which is situated furthest northeast in the investigated area. This zone corresponds to the sandy coastal deposits described below. Zone M–M contains only calcareous benthonic foraminifera. No planktonic species are registered. Most of the foraminifera are shallow water dwelling forms (Skarbø & Verdenius 1986). Both fossils and the lithology indicate that Zone M–M was deposited in an inner shelf environment. The unzoned interval in well 6610/7-1 contains no *in situ* fossils, but seismic correlation indicates that these sections are identical.

Middle to Lower Eocene

Middle to Lower Eocene deposits (Zone M–N) are found in wells 6607/5-1, 6607/5-2, 6506/12-4 and 6610/7-1. A large population of radiolarians, which is generally associated with normal marine conditions, indicates deposition in open marine, relatively deep environments (probably middle to outer shelf).

Upper Paleocene

Upper Paleocene deposits (Zone M–O) are only registered in well 6610/7-2. Pyritized diatoms dominate the fossil assemblage. No foraminifera are registered. The absence of calcareous fossils is probably due to carbonate dissolution. This section was probably deposited in a deep basin with restricted vertical circulation and low oxic to anoxic bottom conditions.

Lithology and lithostratigraphy

The Pleistocene and Upper Pliocene correspond to the Naust Formation. These sections consist of clay-rich diamicton interbeded with unconsolidated coarse- to medium-grained sand. Subangular to angular pebbles of mostly crystalline and some sedimentary rocks occur throughout these sections.

The glaciomarine sediments of the Vøring Plateau have been studied by Jansen (1991, 1993, 1995) and Jansen & Sjøholm (1991), and the results of these investigations provide the best inferences concerning the maximum age of the Naust Formation in these wells. There are traces of ice-dropped material in sediments as old as nearly 12 Ma on the Vøring Plateau. The frequency of such ice-rafted material increases during the period 6.5 to 5.5 Ma, which correlates with the Messinian Stage. The frequency of ice-dropped material remains relatively low, between 5.5 Ma and 2.6 Ma, but the great increase in the supply of ice-dropped material after about 2.6 Ma reflects the marked expansion of northern European glaciers (Fig. 16). This age is considered the maximum age of the Naust Formation in the investigated wells.

The Upper to Middle Miocene corresponds to the Kai Formation. The sediments of this formation are more consolidated than the sediments of the Naust Formation. The sections consist primarily of claystone with small portions of sand and silt. A few crystalline pebbles are found in the upper part of the sections, but these are probably caved.

The Lower Oligocene sections contain mostly sand and pebbles. In the section in well 6610/7-1 and in the upper part of the section in well 6610/3-1 the sand and pebble grains are rust-stained. The lower part of the section in well 6610/3-1 is not oxidized and contains a grey, mica-rich sand. These sections form a part of extensive deposits which extend along the mid-Norwegian coast from Møre to Lofoten (Rokoengen et al. 1995). These deposits are mapped and described by Bugge (1980), Bugge et al. (1984), Askvik & Rokoengen (1985), Rokoengen et al. (1988; 1995), Gustavson & Bugge (1995) and Henriksen & Vorren (1996). The deposits have been given the informal names Frøyrygg Formation (Askvik & Rokoengen 1985) and Molo Formation (Gustavson & Bugge 1995), and according to Rokoengen et al. (1995) classified as delta-like coastal deposits, probably formed in a wave-dominated environment with extensive long-shore drift.

The Middle to Lower Eocene corresponds to the Brygge Formation. These sections consist primarily of claystone. In well 6607/5-1 there are also some limestone beds.

The Upper Paleocene corresponds to the Tare Formation. This section consists primarily of claystone with smaller portions consisting of volcanic tuff.

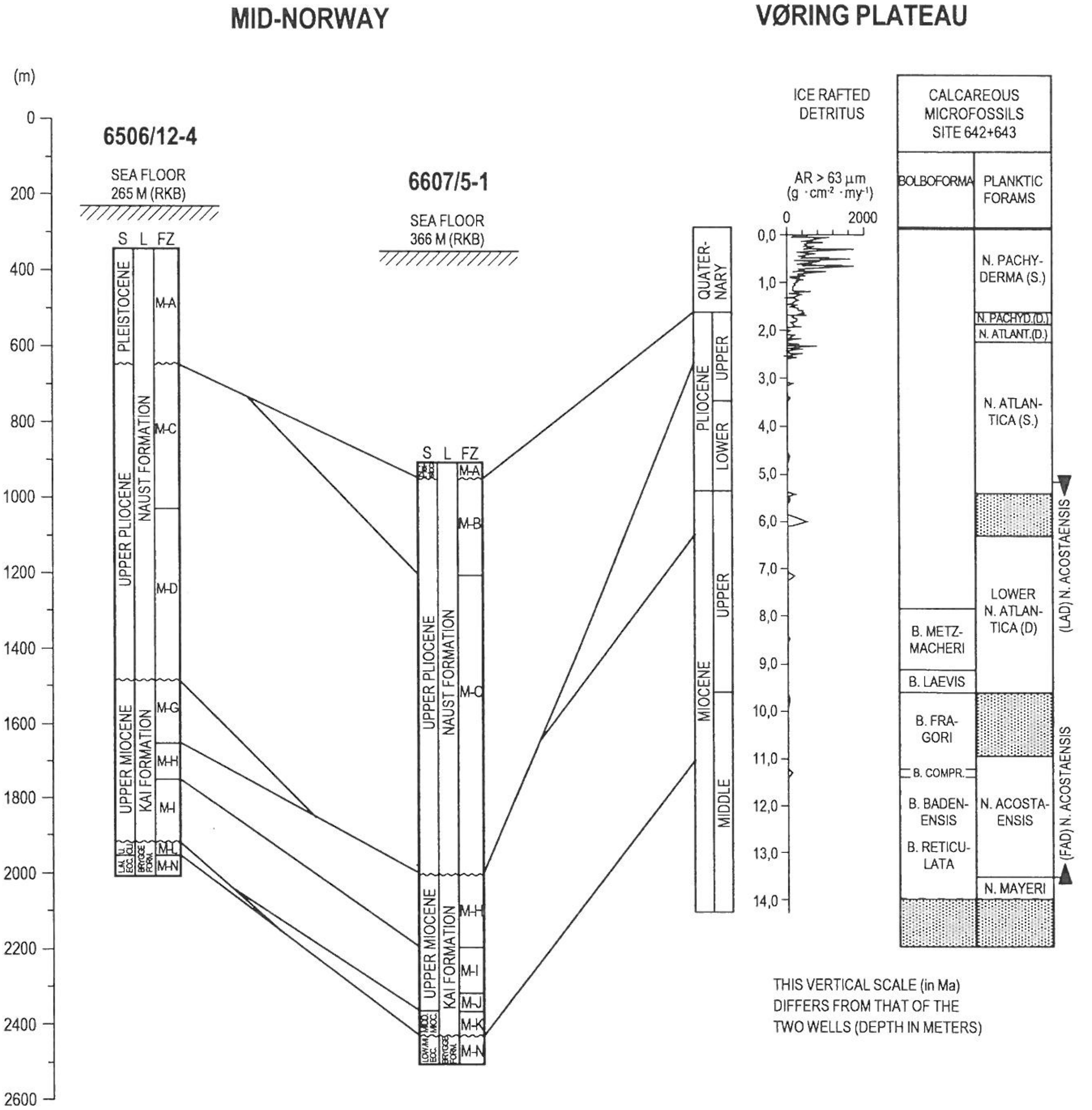


Fig. 16. Correlation of Vøring Plateau ODP sites and the stratigraphy of wells 6506/12-4 and 6607/5-1. The IRD curve is after Jansen & Sjøholm (1991) and Jansen (1995). The fossils zones of the ODP sites are after Spiegler & Jansen (1989) and Müller & Spiegler (1993). S = series/subseries, L = lithostratigraphic formations, FZ = fauna zones, AR = accumulation rate, m RKB = meters below rig floor.

Summary and discussion

During the Late Pliocene, thick, glacially derived deposits prograding from the east were laid down on the continental margin off Mid-Norway. In most areas, a hiatus is present between the Upper Pliocene and the Pleistocene. This hiatus is visible on seismic sections as a distinct reflector. Parallel and discontinuous reflectors in the Pleistocene truncate the prograding Upper Pliocene reflectors. Far west on the continental margin the base Pleistocene reflector becomes less distinct, and a truncation is not visible. In well 6607/5-1 on the Utgard High there is only a small hiatus between Upper Pliocene and Pleistocene.

Differences in Pliocene and Pleistocene deposition patterns are probably the result of changes in glaciation cycles. During the glacial period prior to 1 Ma, glacial cycles had durations spanning approximately 41 k.y. After approximately 1 Ma, 100 k.y. cycles were dominant. Both glacials and interglacials were more intense during the last period (Prell 1982, Ruddiman et al. 1986 and Berger & Jansen, 1994). During the period prior to approximately 1 Ma, the ice cap which covered Fennoscandia probably extended down to the coast in most areas. During the period subsequent to approximately 1 Ma, glaciers extended at times over the continental shelf and transported sediments over greater distances. Erosion between the Upper Pliocene and the Pleistocene was probably caused by either the advance of the glacial front or glacial-isostatic drop in sea-level. The advance of the glacial front is probably the most important transport mechanism for material from the land areas to the continental shelf, and the parallel and discontinuous reflectors seen in the Pleistocene section probably correspond to sediments laid down by glaciers.

In wells 6506/12-4 (Halten Terrace) and 6607/5-1 (Utgard High) Upper Pliocene deposits lie unconformably on the Upper Miocene. The lowermost Upper Pliocene and Lower Pliocene are absent in all of the investigated wells. In wells 6610/7-1 and /7-2 (Nordland Ridge) and 6607/5-2 (Utgard High) Upper Pliocene deposits rest unconformably on Paleogene sediments. In the northern North Sea the deposits from the lowermost Upper Pliocene to uppermost Upper Miocene are also absent (Eidvin & Riis 1992). In the western Barents Sea the Upper Pliocene lies unconformably on Lower Tertiary deposits (Eidvin et al. 1993a, 1994). In the central North Sea most of the Neogene and Upper Paleogene sections are present (Eidvin et al. 1993b). Vail & Hardenbol (1979) describe an extensive drop in global sea levels during the period 4.2–2.8 Ma. This regression appears to have caused an erosion of most of the Norwegian continental shelf, with the exception of the deeper areas in the Central and Viking Graben.

In well 6506/12-4 the Upper Miocene rests unconformably on Upper Oligocene-Lower Miocene deposits. In well 6607/5-1 Upper Miocene and uppermost Middle Miocene deposits lie unconformably on Lower to Middle Eocene deposits. Miocene sediments are not present in any of the wells on the Nordland Ridge. In well 6610/7-2 deposits younger than Late Paleocene and older than Late Pliocene are absent. In wells 6610/7-1 and 6610/3-1 coastal Lower Oligocene deposits are present. These deposits extend almost as far west as well 6610/7-2 (Fig. 6).

In connection with the seismic mapping of the eastern part of the mid-Norwegian continental shelf, IKU Petroleum Research cored the coastal deposits with a vibracorer. The vibracoring disturbed the sediments during the sampling, producing a blend of Holocene and late Weichselian foraminifera (dominant) and Oligocene and Eocene dinoflagellates. However, the Oligocene dinoflagellates were thought to be *in situ* fossils (Skarbø et al. 1983). Subsequently, it has been suggested that the coastal deposits correspond to the most proximal and oldest part of the Upper Pliocene sedimentary wedge.

Seismic profiles through this area show that Upper Pliocene prograding deposits onlap the Lower Oligocene coastal deposits (Figs. 6, 7). The coastal deposits probably represent erosional remnants. It is reasonable to assume that the these deposits have extended further east and probably have been eroded in three main phases: (1) During a regression caused by a drop in sea level at about 29 Ma (Vail & Hardenbol 1979). (2) During a regression in mid-Middle Miocene caused by regional uplift (Riis 1996). This phase is represented by a hiatus between the Upper Miocene and Upper Oligocene in well 6506/12-4, and in wells in the northern North Sea as a hiatus between the Upper and Lower Miocene (Eidvin & Riis 1992). In wells in the central North Sea this phase is represented by a seismic reflector with no discernible or only a small hiatus present. This reflector is accurately dated to 12.5 Ma (Eidvin et al. 1993b). (3) During the Late Pliocene and Pleistocene; first during the period with a drop in sea level between 4.2 and 2.8 Ma (Vail & Hardenbol 1979), later during glacial phases in the Late Pliocene and Pleistocene. Many rust-stained pebbles, which probably come from the Oligocene coastal sediments, are registered in the Upper Pliocene deposits in wells 6610/7-1 and /7-2.

Below the coastal deposits in well 6610/7-1 there are deposits of Early to Middle Eocene age.

Haflidason et al. (1991) investigated a cored geotechnical borehole from the Draugen Field (Haltenbanken). This borehole extends through the base Pleistocene angular unconformity and penetrates a seismic reflector in the prograding sequence below. The cores from this borehole were subjected to paleomagnetic, amino acid and foraminiferal analyses. The base of the borehole is dated to 1.1 Ma. However, following the dated reflector at the base of the borehole westwards, it is obvious that much of the Upper Pliocene wedge is situated above this reflector (Rise et al. 1988; Rokoengen et al. 1995). These Upper Pliocene deposits correspond to sediments which have been dated to 2.6–2.3 Ma in our investigations.

Sejrup et al. (1995) investigated a similar cored borehole from the Troll Field in the northern North Sea. This borehole only just penetrates the base Pleistocene angular unconformity in this area. The same investigations have been performed on the cored material from this borehole as on the Draugen Field. The base of this borehole is also dated as 1.1 Ma. In this area Pleistocene deposits rest unconformably on Upper Oligocene deposits, and in the west on prograding deposits of the Upper Pliocene. A comparison between the situation on the mid-Norwegian shelf after Haflidason et al. (1991) and the situation in the northern North Sea after Sejrup et al. (1995), would indicate that the Pliocene/Pleistocene sedimentary wedges are much younger on the mid-Norwegian continental shelf than in the northern North Sea. Seismic mapping over these areas indicates that this is not the case (F. Riis; pers. comm.) This suggests that the dating of the Draugen borehole is incorrect, or that the dated material is not from the anticipated seismic reflector.

Based on biostratigraphical investigations and oxygen isotope measurements of wells 6507/10-1 and 6407/1-2 on the Halten Terrace and well 6610/7-1 on the Nordland Ridge, Poole & Vorren (1993) suggest that the oldest parts of the sedimentary wedges are older than

Late Pliocene. They suggest that most of the wedges are of Middle Pliocene age. They state that the oldest part of the wedge system is found in well 6610/7-1, and this is given an Early Miocene to Early Pliocene age. This interval corresponds to two fossil-barren intervals designated 'Barren Zones 1 and 2'. Our investigations of the same well show that 'Barren Zone 2' corresponds to our 'unzoned' interval, which by seismic correlation is dated as Lower Oligocene. 'Barren Zone 1' corresponds to the base of the Upper Pliocene wedge. Our investigation of 'Barren Zone 1' shows that this interval contains a moderately rich Upper Pliocene foraminiferal fauna, and that the sediments are of glaciomarine origin. These observations are supported by results from the neighboring well 6610/7-2 where this section has sidewall core coverage.

According to Poole & Vorren (1993) there is a sequence below 'Barren Zone 2' in well 6610/7-1 containing Early Miocene fossils. We have examined this interval in detail, and have not found any of the described foraminifera. However, below this interval we have recorded a rich fauna of Lower–Middle Eocene radiolarian and agglutinated foraminifera (Zone M–N). We were unable to find any Miocene fossils in well 6610/7-2, either. If an Early Pliocene/Miocene age is correct, the foraminifers found in well 6610/3-1 are reworked. Reworking cannot be ruled out, but none of the analyzed tests showed any sign of wear, thus indicating that reworking is unlikely. Some of the palynomorphs are reworked, but these are much smaller and more buoyant and consequently more readily transported.

The theory of Poole & Vorren (1993), that the younger parts of the Pliocene wedge are of Middle Pliocene age, is based on the occurrence of the foraminifers *Florilus boueanus*, *Cibicidoides limbatosuturalis* and *Cancris auriculus* in well 6407/1-2. *F. boueanus and C. auriculus* are known from the Upper Oligocene to Lower Pliocene in the North Sea (King 1989), and *C. limbatosuturalis* is known from Upper Miocene to lower Upper Pliocene in the same area (King 1989). None of these foraminifers were recorded in our investigation of sediments of the same age. Therefore, if these forms are present in other parts of the Pliocene wedge, it must be the result of reworking.

Henriksen & Vorren (1996) have given the coastal deposits, which 'Barren Zone 2' after Pool & Vorren (1993) is a part of, two alternative ages: (1) An Early Oligocene age based on a lecture and personal observations comprising preliminary results from this work; and (2) an Early Pliocene/Miocene age based on Poole & Vorren (1993).

The youngest part of the Kai Formation is represented by Zone M–G in well 6506/12-4. In Eidvin & Riis (1991) this zone was given an uncertain Late Miocene to Early Pliocene age. The re-examination of the planktonic foraminifera shows the presence of the lower *N. atlantica* (dextral) zone of Spiegler & Jansen (1989), confirming a Late Miocene age.

Acknowledgements. – The authors acknowledge Geco-Prakla for permission to publish seismic lines and extend their thanks to Bjørg Ruus, Sigrun Torrissen and Finn Moe for their areful and accurate technical assistance during this project. They also thank Eystein Jansen, Finn Eidvin, Robert Williams, Paul Grogan, Astrid Larsen, Robert M. Goll, Gøran Åberg, Helge Stray and Bjørn Pilskog for their cooperation. Geoff D. Corner, Dorothee Spiegler, Joar Sættem, Jørn Thiede and Martin Weinelt reviewed the manuscript and offered numerous suggestions.

Manuscript received December 1996

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Paper 5:

Chronology of Tertiary fan deposits of the western Barents Sea: implications for the uplift and erosion history of the Barents Shelf

Marine Geology, 112 (1993) 109–131
Elsevier Science Publishers B.V., Amsterdam

Chronology of Tertiary fan deposits off the western Barents Sea: Implications for the uplift and erosion history of the Barents Shelf

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(Received June 29, 1992; revision accepted January 12, 1993)

ABSTRACT

Eidvin, T., Jansen, E. and Riis, F., 1993. Chronology of Tertiary fan deposits off the western Barents Sea: Implications for the uplift and erosion history of the Barents Shelf. *Mar. Geol.*, 112: 109–131.

A combined biostratigraphic and seismic study was performed on three holes drilled in the western Barents Sea. Two holes penetrate the thick sedimentary wedge which forms a large fan located off a trough on the Barents Sea Shelf, the Bjørnøyrenna Fan. The study shows that the fan was built over a short time span in the late Pliocene–Pleistocene, mainly due to glacial erosion of the Barents Shelf region. This contrasts earlier age assignments which concluded that fan-deposition started in the Oligocene. The results have a major impact on the understanding of trough mouth fan formation and has important bearing on the history of the sedimentary basins of the Barents Shelf.

Introduction

Thick Tertiary fan deposits cover the Western Margin off the Barents Sea, and are believed to be depocenters for erosion products from Cenozoic uplift and erosion of the Barents Shelf area (Spencer et al., 1984; Nøttvedt et al., 1988; Vorren et al., 1991). The fans are easily identified as positive bathymetric features extending the continental slope westward off the western margin of the Barents Sea. Major portions of the upper sedimentary sequence on the adjoining Barents Shelf are evidently removed. Beneath the relatively thin Pleistocene cover, only sediments of Eocene age or older are observed (Sigmond, 1993). Vorren et al. (1991) and Nøttvedt et al. (1988) calculated that the volume of sediments contained in the Barents Sea margin fans corresponds to a layer of approximately 1000 m uniform thickness eroded off the adjacent drainage area. Although there are major uncertanties contained in such calculations, they provide a gross estimate pointing to the fans as being formed as a response to major erosion phases on the shelf.

While it is of general interest to date the buildup of the fans in order to better understand their formation history, we undertook the present study also due to the importance of the erosion history for understanding sedimentary basin evolution to aid petroleum prospecting in the Barents Sea. Major uncertainties were inherent in earlier datings of the fans. Different industry consultants arrived at widely different age estimates, leading to very different interpretations of the geological history of the Western Barents Margin. Unpublished consultant reports proposed an Eocene age of the lower part of the wedge. This problem also affects the published literature: Spencer et al. (1984) concluded that the base of the sedimentary wedge (Unit IIIA) is a major hiatus. Sediments above this hiatus appeared to range from Miocene to late Pliocene, which led the authors to conclude that

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the unit boundary could be intra-Oligocene partly based on the same holes as studied in this paper. Nøttvedt et al. (1988) also gave an age of mid-Oligocene for the base of the fan, but provided no new documentation for this assumption. Vorren et al. (1990) used downlap on oceanic crust and magnetic anomalies to date the bottom of the wedge and proposed a mid-Oligocene age. This was later revised by Vorren et al. (1991) who also considered the biostratigraphic evidence reported in this paper. However, Vorren et al. (1991) propose that the lower unit of the wedge is of mid- to late-Miocene age, in contrast to the younger age indicated from our studies, based on downlap on oceanic crust of Anomaly 5 age. The discrepancy with the results provided in this contribution lies in the seismic correlation and the question of whether the lower parts of the wedge are represented in the holes we have studied.

The main reason for the earlier dating discrepancies originates from the large influence of redeposited material in the fan deposits. We tried to overcome this problem by utilizing as many criteria as possible, and employing a critical attitude to material and methods, thereby developing criteria which are robust, disregarding the biostratigraphic information that arises from redeposition.

Our initial hypothesis was that the fans were young, and of Plio-Pleistocene age. This was based on gravity anomaly modelling performed by Fjeldskaar and Riis (1988), and by the similarities in seismic signature with Plio-Pleistocene deposits off middle Norway. This possibility was already pointed out by Nansen (1904), who viewed the bathymetric expression of the fans as a product of glacial erosion and deposition.

We studied holes 7117/9-1 and 7117/9-2 (Fig. 1) from the Senja Ridge, which are the only holes which penetrate the fan deposits in the Barents Sea, and compared the results with hole 7119/7-1 (Fig. 1) which is the closest hole outside of the fans. The results clearly point to the conclusion that the fan deposits are of glacial origin and were deposited in the late Pliocene and Pleistocene. These results have important bearing on the history of uplift and erosion in the Barents Sea region, with major implications for attempts to model the sedimentary basin evolution of the Barents Shelf.

Seismic interpretation

Two large fans are identified as sedimentary wedges extending westward off the western Barents Sea. They are situated off shelf troughs; one off Stordfjordrenna (Storfjordrenna Fan), and a larger fan off Bjørnøyrenna (Bjørnøyrenna Fan; Fig. 1). The margin is covered with a regional seismic grid, in parts also with detailed seismics. Only few lines extend far enough westward to cover oceanic crust. In this study we emphasize the seismic mapping of the bottom of the fans, rather than providing interpretations of internal fan sequences.

Figure 2 shows the distribution of the Bjørnøyrenna Fan depicted as the thickness of the sedimentary wedge. This is defined seismically as the thickness of sediments between the bottom of the fan and the Upper Regional Unconformity (URU). This unconformity truncates the Bjørnøyrenna Fan in its eastern part, thereby defining the eastern boundary of the fan close to Hole 7119/7-1 (Vorren et al., 1989; see also Fig. 8). The area of the two holes on the Senja Ridge is covered by a 1 × 1 km seismic grid of reasonable good quality. Figure 3 shows a seismic tie line between the holes. Based on the detailed industry seismic grid available to us, it has been straightforward to tie the local seismics to the regional seismic grid, thereby tying the reflectors from the holes to the regional reflector system and thereby to the main depocenter of the Bjørnøyrenna Fan at 72°N, north of the holes. Figures 4 and 5 illustrate the tie to the main sequences in the fan north of the holes. The fan is distinguished by the thick prograding and undeformed sediments defined by the lower unconformity (Reflector 3).

Seismic lines through the holes point to two main unconformities within the fan (Figs. 6 and 7): The upper is URU (Upper Regional Unconformity, Vorren et al., 1990), or Reflector 1, which is located at about 0.67 s, or 600 m, in both holes. Beneath this is a pronounced sequence boundary (Reflector 2 in Figs. 6 and 7) at 0.98 s in Hole 7117/9-1 and at 0.92 s in Hole 7117/9-2, corresponding to subbottom depths of 910 and 860 m, respectively. Reflector 2 is defined by its truncation of the underlying clinoforms, and it can be followed far westward before defining a paleo-

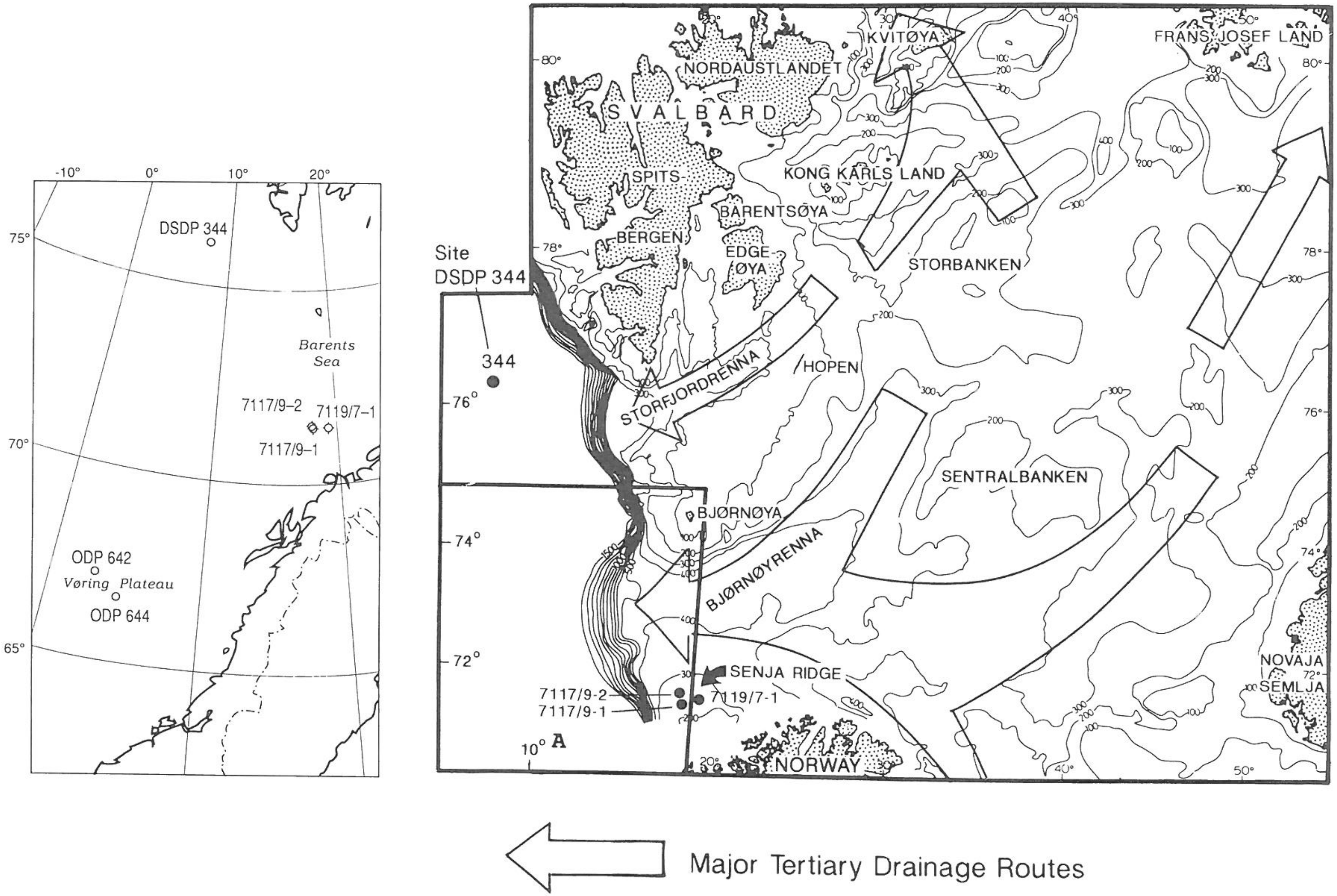


Fig. 1. Map of the Barents Sea and the Norwegian Sea with holes indicated. Also indicated are ODP/DSDP sites referred to in the text. Box *A* defines area shown in Fig. 2. Tertiary drainage routes are according to Nøttvedt et al. (1988).

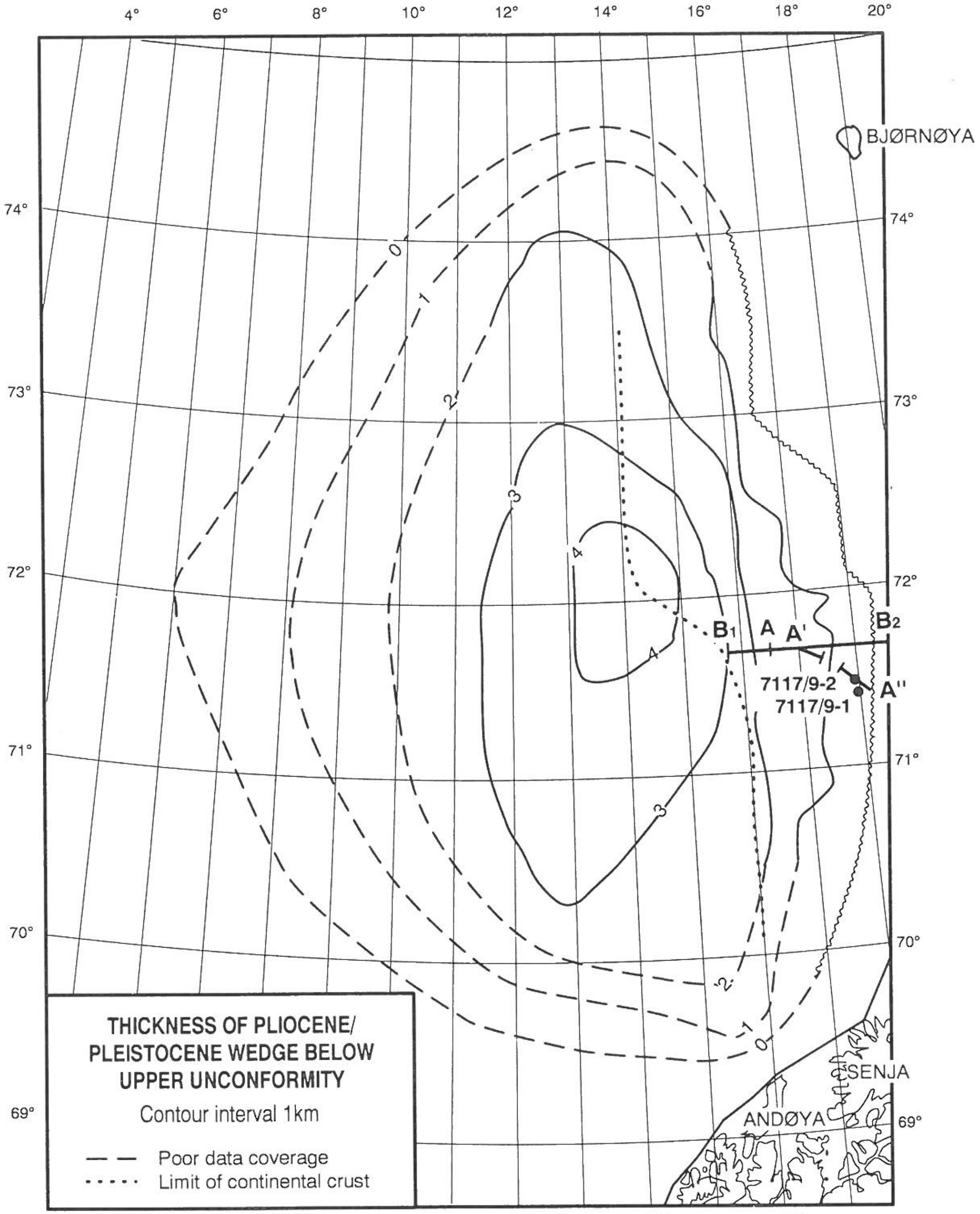


Fig. 2. Areal distribution and thickness in kilometers, of the Bjørnøyrenna Fan. Holes and the seismic lines of Figs. 4 and 5 are indicated.

"shelf-edge". To the east Reflector 2 cuts the bottom of the fan and defines the bottom of deep erosional channels in the Tromsø Basin. These erosional channels are better defined by shallow seismics, and further document the erosional character of Reflector 2. The lower boundary of the fan (Reflector 3 in Figs. 6 and 7) is also a marked sequence boundary which defines an erosional

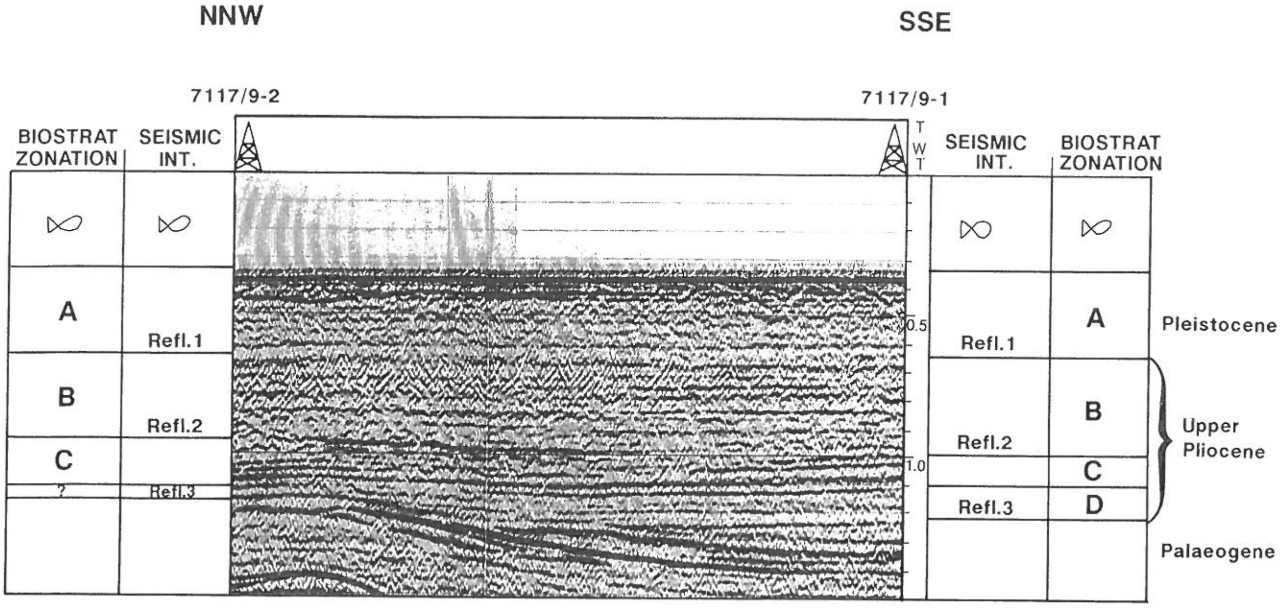


Fig. 3. Seismic tie line between holes 7117/9-1 and 7117/9-2.

relief on the Senja Ridge. This reflector is tied into the regional seismics (Figs. 4 and 5) and documents that most of the fan is contained in the two holes we studied. The base of the wedge is not easy to define with certainty seismically where it overlies oceanic crust. Existance of slightly older sequences than the ones defined in our study thus cannot be ruled out. The reflectors correspond to biostratigraphic zonal boundaries discussed below (Fig. 3). Sættem et al. (1992) studied the northern part of the Bjørnøya wedge west of Bjørnøya and reported deep erosional channels at the base of their Unit A, which corresponds to Reflector 3 in this work. Thus the formation of deep erosional channels apparently happened earlier in the Bjørnøya area than further south in the Tromsø Basin.

Hole 7117/9-2 is located at a higher structural position in the Senja Ridge than Hole 7117/9-1 and the reflectors at the bottom of the Fan onlap towards this high. On Fig. 3 which is the seismic tie line between the holes, this is documented by the lower 50–60 ms of Hole 7117/9-1 being absent from Hole 7117/9-2. Further west there is no clear erosional boundary of the Fan, and it is thus less easy to define the lower boundary based on seismics. The error range for the determination of the bottom of the fan here is about 0–50 ms.

Figure 4 documents the seismic correlation of the units from the holes to the main depocenter of the wedge. Figure 5 shows an interpreted line extending from the shelf break, and documents the main units of the wedge. The interpretation along the part between seismic sections GBW 88-T4 and GBW 88-T3 (Fig. 4), which we do not show in detail in this figure, is regarded as relatively straightforward. Note the truncation of Paleocene–Eocene strata at the Senja Ridge, close to Hole 7117/9-2 and the downlap of the wedge further to the northwest onto supposedly Oligocene–Miocene strata.

Hole 7119/7-1 lies east of the other holes and does not contain fan sequences (Fig. 8).

Biostratigraphy

Material and methods

For biostratigraphic studies we only had cuttings at our disposal. This is far from the ideal material to work with and limits the biostratigraphic precision, both due to problems of identifying the exact sub-bottom depth to which a certain assemblage belongs and because of potential downhole contamination by sidewall fragments falling in

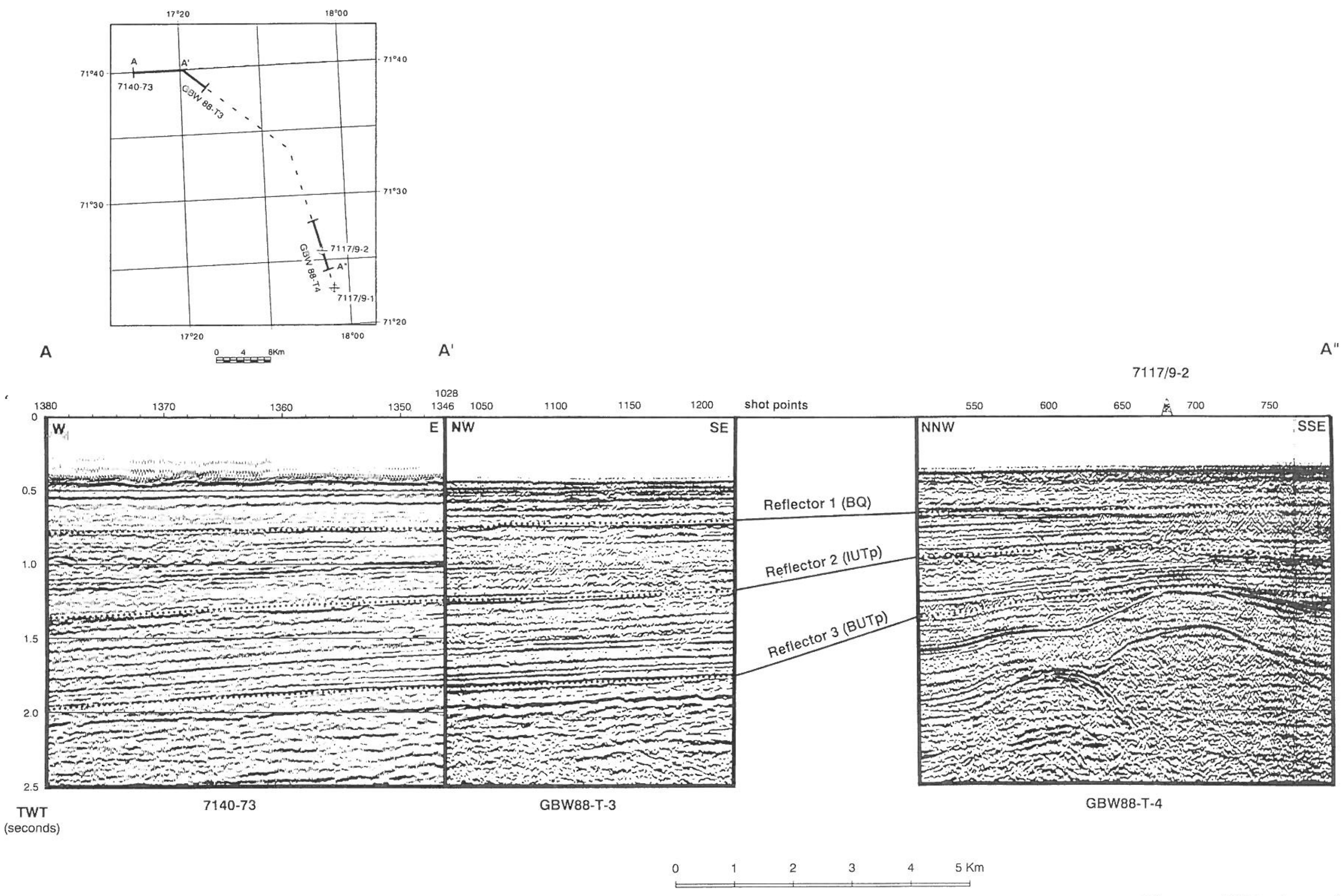


Fig. 4. Seismic line ties between Hole 7117/9-2 and the main depocenter for the Bjørnøyrenna Fan. *BQ* = base Quaternary, *IUTp* = Intra upper Pliocene, *BUTp* = base of upper Pliocene.

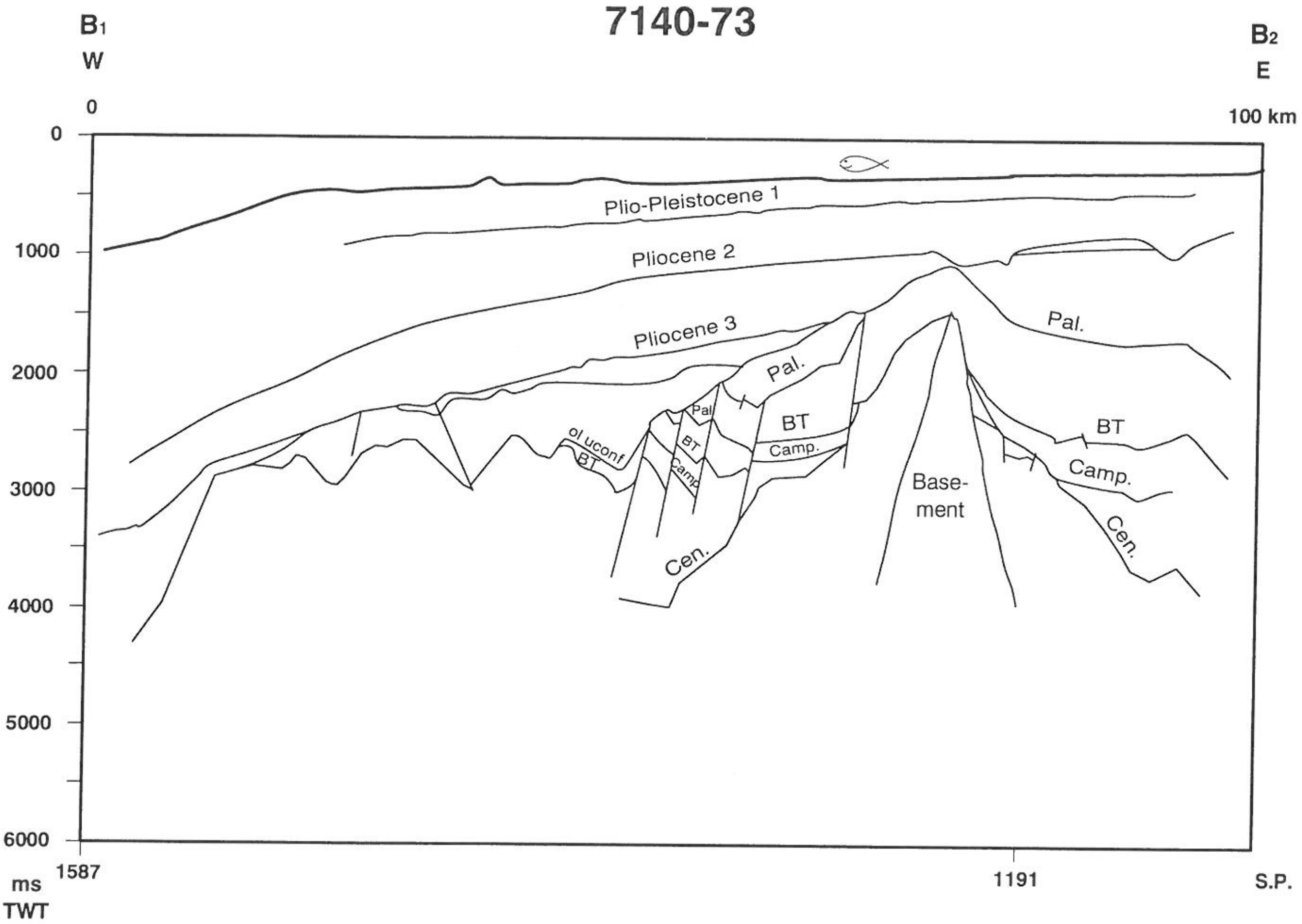


Fig. 5. Geoseismic section from the shelf edge into the wedge. The location of the line is shown on Fig. 2.

from uncased sidewalls. Because of this constraint, our interpretation is limited to markers and assemblages which are clearly defined in both holes and mark major biostratigraphic boundaries.

For the analyses 50–100 g material was used. Unconsolidated material was soaked in water and wet sieved. Consolidated material was dissolved in diluted hydrogen peroxide solution. Microfossil identifications were done in the 0.1–0.5 mm fraction. Whenever possible 300 individuals were counted in each analysis. In order to better identify the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity separated in heavy liquid.

In Hole 7117/9-1 one sample every 10 m was analyzed in general. In the two other holes we analyzed most samples at 20 m interval. In important sequences, denser sample spacing was employed.

Results

Biostratigraphic results are reported in the range charts of Figs. 9–11. Further documentation can be found in Eidvin and Riis (1989).

Based on these charts the assemblages were grouped into assemblage zones based on characteristic/frequent species. Most emphasis is placed on planktonic and benthic foraminifers.

Holes 7117/9-1 and 7117/9-2

The upper approximately 100 m of sediment were not sampled during drilling. The biostratigraphy of the upper 600–700 m in these holes is rather straightforward and unproblematic. The foraminiferal assemblages are dominated by Pliocene and Pleistocene forms with minor contribution from microfossils of late Cretaceous and early Paleogene age.

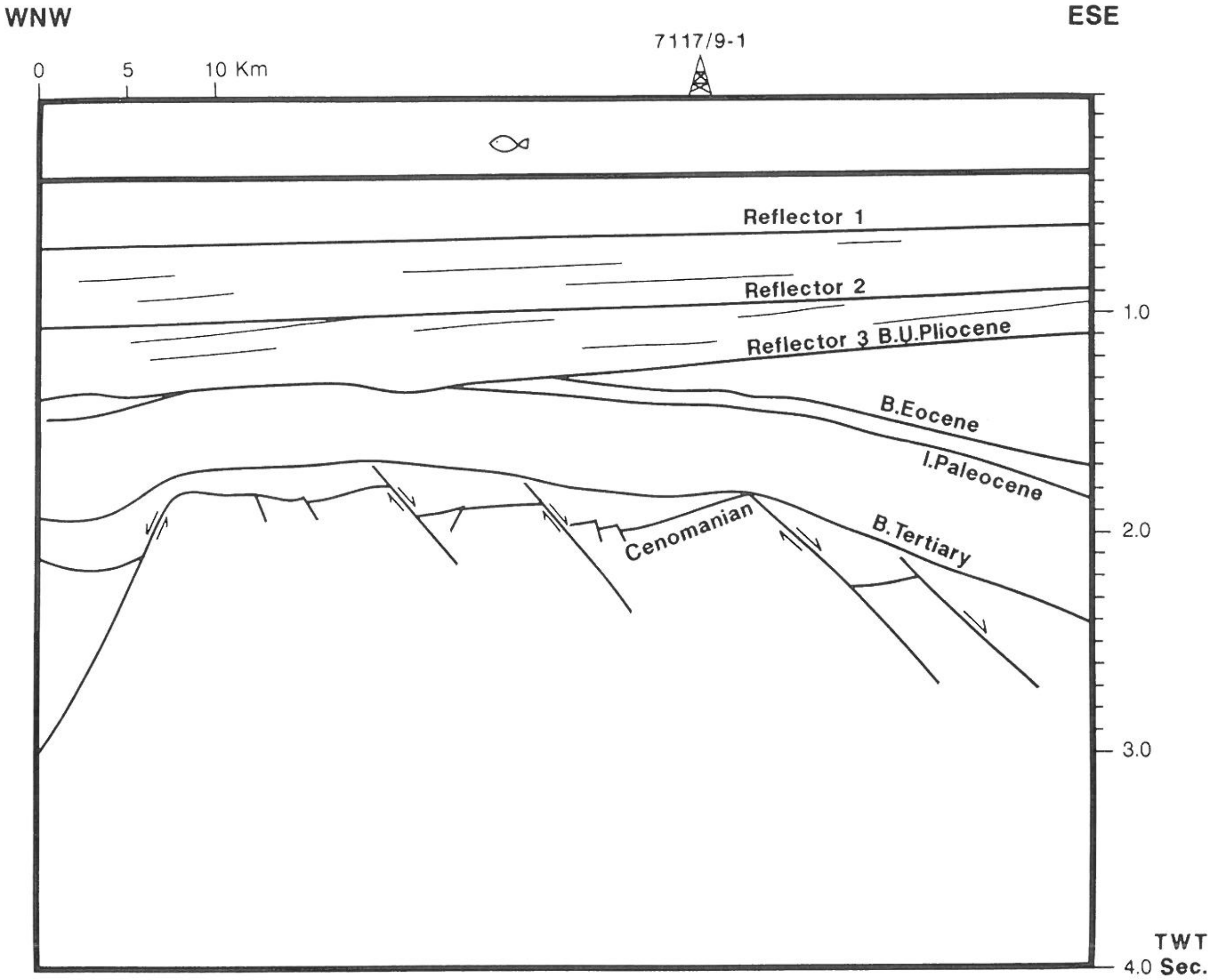


Fig. 6. Geoseismic section through Hole 7119/9-1.

Below this level and down to 1180 m in Hole 7117/9-1 and 1120 m in Hole 7117/9-2, the situation is more complicated. Eocene microfossils dominate in most levels. This was the background for the earlier unpublished industry reports assigning an Eocene age to the onset of fan build-up. There is, however, a strong influence of Plio–Pleistocene forms, somewhat less abundant fossils from the late Cretaceous, and also a mixture of fossils ranging in age from late Jurassic to Miocene. If we exclude all other fossils from consideration except the Plio-Pleistocene forms, we note that these comprise a depth zonation which is clearly identifiable in both holes at almost equal sub-bottom depths. It is possible to distinguish four different zones defined by benthic and planktonic foraminifers and one species of sponge spicules. In Hole 7117/9-1 all four zones are present, in Hole 7117/9-2 only the upper three are found. The upper limits of the zones occur at equal sediment depths in both holes. This indicates that the zonation is primary. It is unlikely to have such a zonation at equal depths in two separate holes if the Plio-Pleistocene fossils were introduced by downhole contamination. Furthermore: the zonal boundaries correspond with the main internal reflectors in the sequence and thus appear to reflect the main depositional sequences (Fig. 3), within the uncertainty imposed by the conversion of seismics to meters below sea floor. It is also

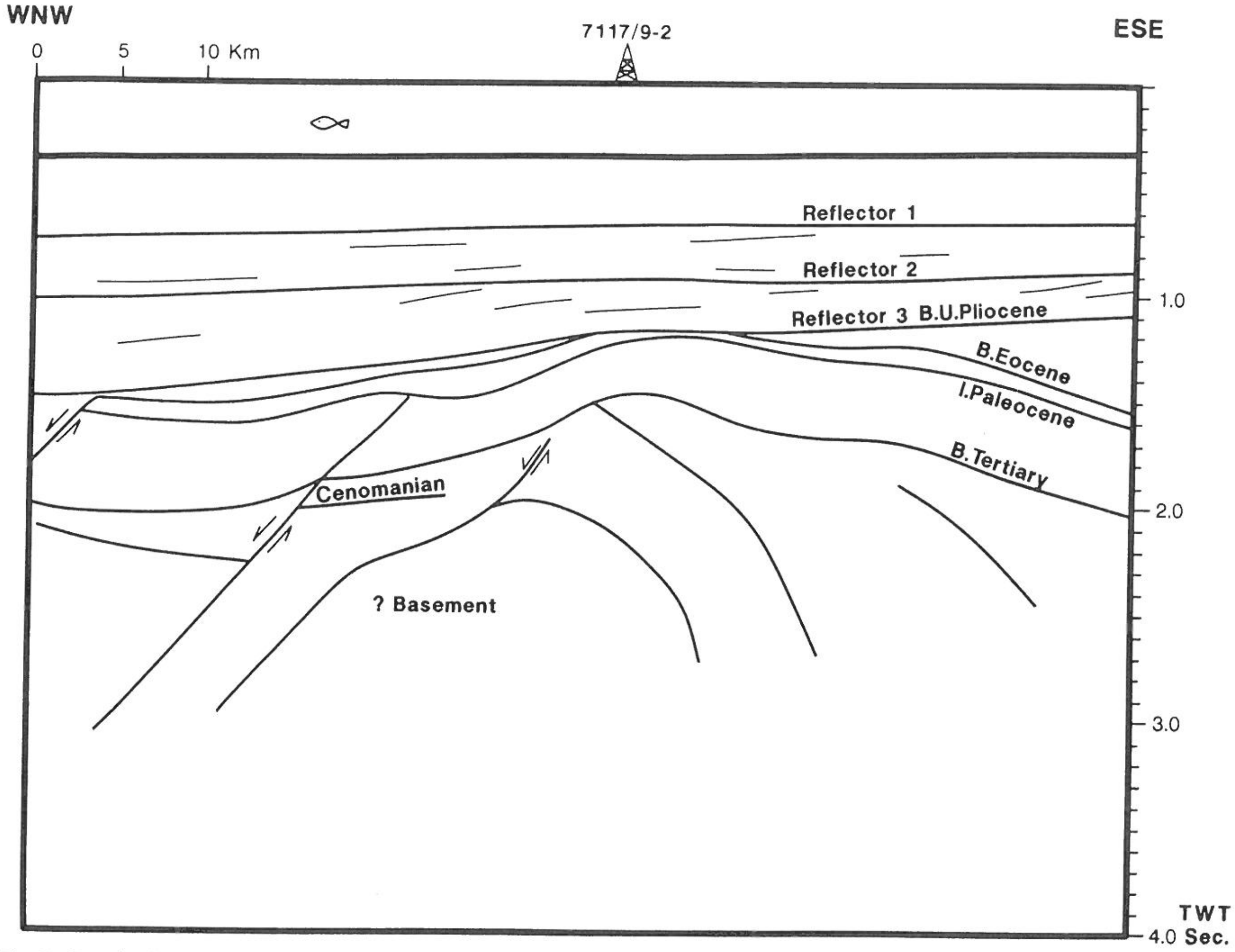


Fig. 7. Geoseismic section through Hole 7119/9-2.

unlikely that this is the case should the Plio-Pleistocene assemblages be a result of random downfall.

We define these zones as follows:

Zone A: Neogloboquadrina pachyderma *(sinistral)*–Islandiella islandica *Zone*

Definition: Frequent occurrence of *N. pachyderma* sin. encrusted form and common occurrence of *I. islandica* (Figs. 9, 10 and 12).

The zone ranges from 350 to 610 m in Hole 7117/9-1 and from 360 to 600 m in Hole 7117/9-2. The zone covers the sediments above Reflector 1 in both holes (Fig. 3).

N. pachyderma sin. which is common to frequent in this zone, is the dominant foraminifer species, defining the last 1.7 Ma interval in DSDP/ODP holes from the Norwegian Sea and the northernmost North Atlantic. The first frequent occurrence of this species in its encrusted variety is at 1.7 Ma, and it is only occurring very sporadically before this time (Weaver and Clement, 1986; Spiegler and Jansen, 1989). This indicates that Zone A is younger than 1.7 Ma.

The benthic calcareous foraminifers of this zone are all species known from Plio-Pleistocene deposits. None are extinct. All samples contain mixtures of arctic and boreal forms, probably mixed from levels representing different climatic states within glacial–interglacial sequences. Each sample represents 10 m of drilling and will include a mixture of what was represented in that interval, hence mixing of different paleoenvironmental indicators

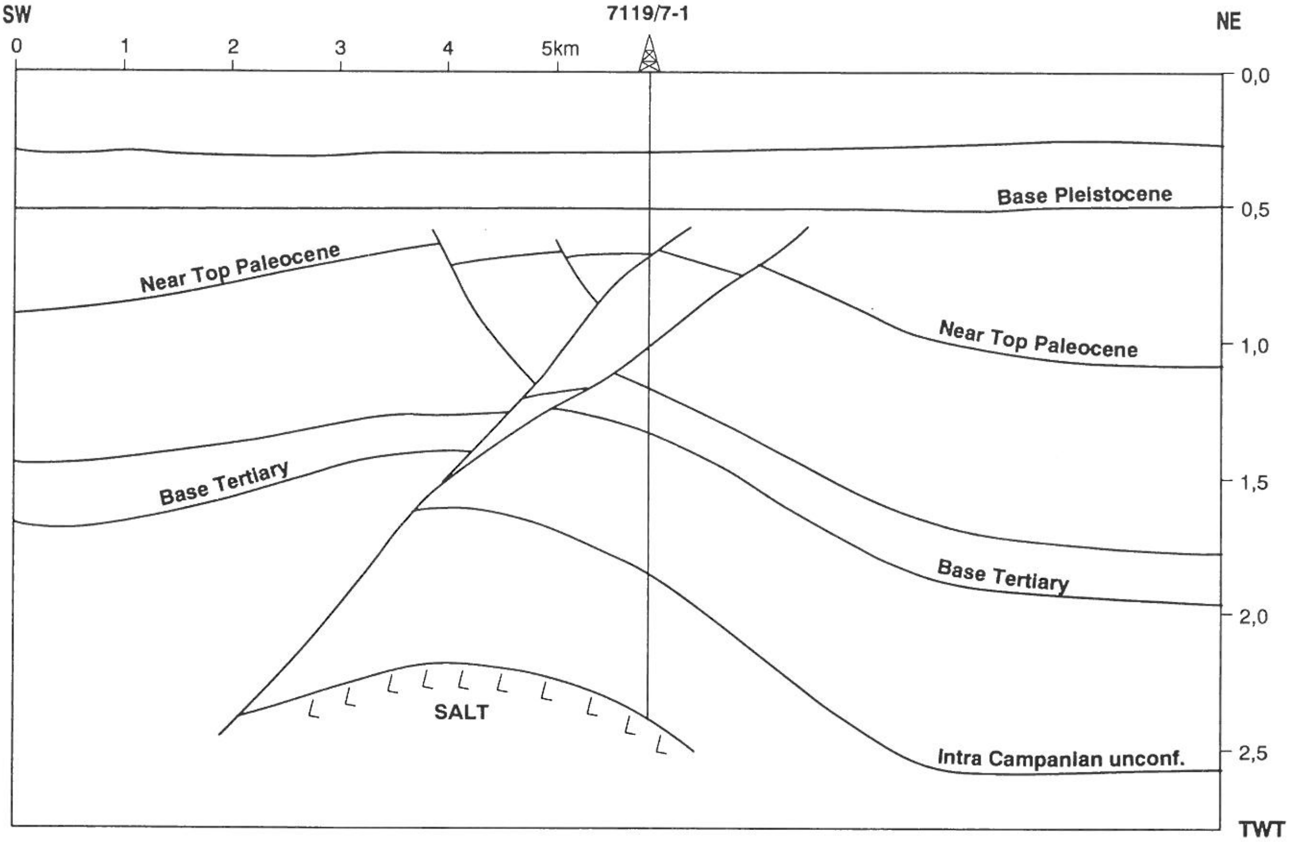


Fig. 8. Geoseismic section through Hole 7119/7-1.

is highly possible. The samples were taken so as to represent as closely as possible an average of the drilled sequence. *I. islandica*, which is limited to this zone, is described from Pleistocene deposits from Arctic Canada (Feyling-Hanssen, 1986) further indicating a Pleistocene age for the zone.

The Cretaceous–Eocene fossils found in the zone are believed to be redeposited during the erosion phases that led to fan formation. This is supported by the worn and fragmented appearance of these fossils.

Zone B: Cibicides grossus *Zone*

Definition: Common occurrence of *C. grossus* (Figs. 9, 10 and 12).

The zone ranges from 610 to 900 m in Hole 7117/9-1 and 600 to 880 m in Hole 7117/9-2. It covers the sediments between Reflector 2 and 1 in both holes (Fig. 3).

Common occurrence of *C. grossus* is almost exclusively limited to this zone and it occurs systematically throughout the zone. According to King (1989), this species is found in late Pliocene deposits in the southern North Sea where it became extinct just before the Pliocene/Pleistocene boundary. Further to the north in the North Sea it may have become extinct somewhat later, perhaps slightly above the Pliocene/Pleistocene boundary (King, 1989). Upper Pliocene deposits from Arctic Canada also contain *C. grossus* (Feyling-Hanssen, 1986). As for Zone A, the remaining Plio-Pleistocene calcareous foraminifers are all extant and mixtures of species of arctic and boreal affinities.

N. pachyderma sin. appears only sporadically in the zone. This is the same pattern of appearance which is noted in late Pliocene sediments from the Vøring Plateau (Spiegler and Jansen, 1990).

In contrast to Zone A, agglutinated foraminifers are more common in Zone B. Most particularly we find *Spiroplectammina spectabilis* and *Reticulophragmium amplectens*. According to King (1989) *S. spectabilis* is found in Paleocene and

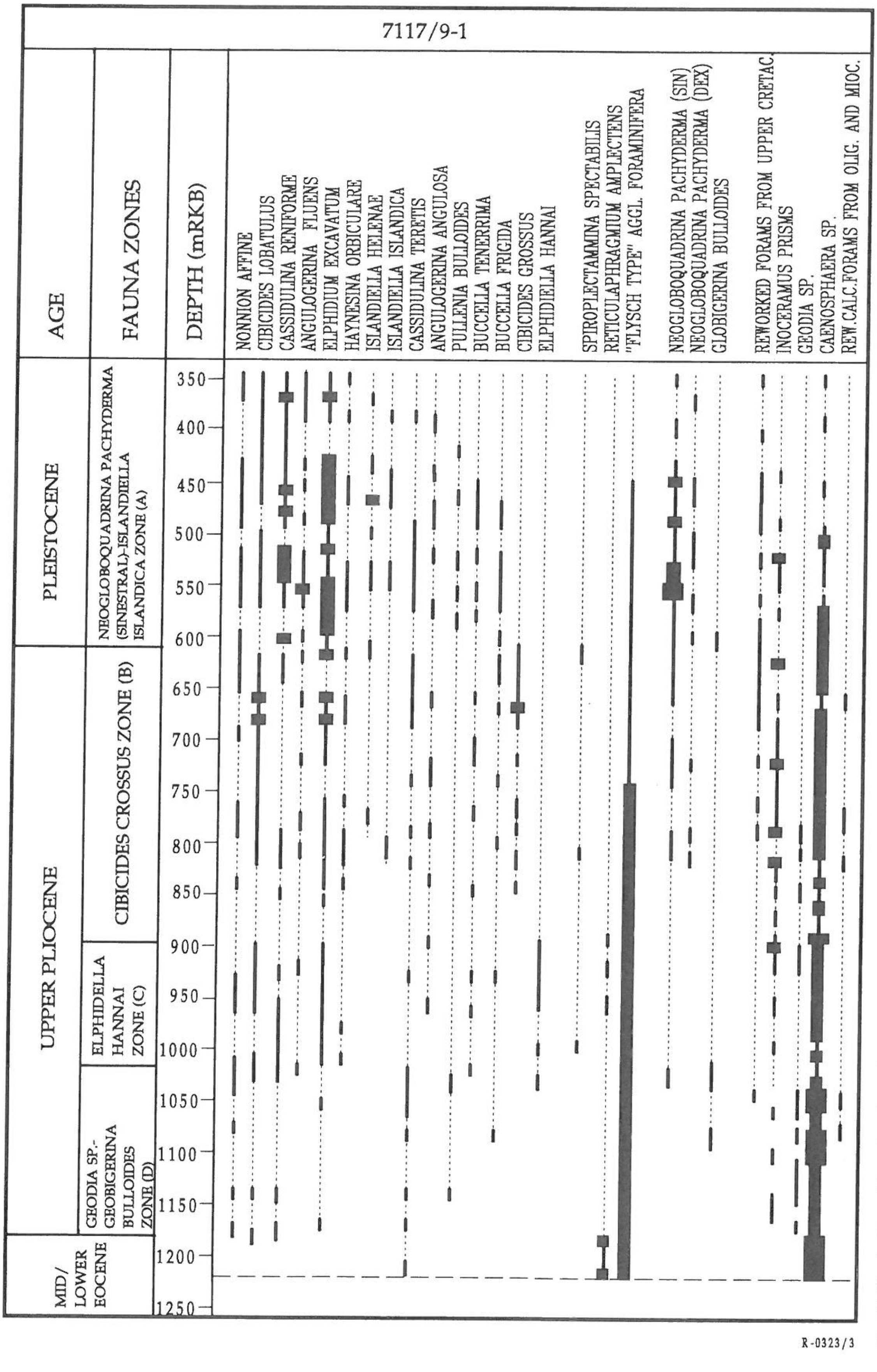


Fig. 9. Biostratigraphic range chart for Hole 7117/9-1.

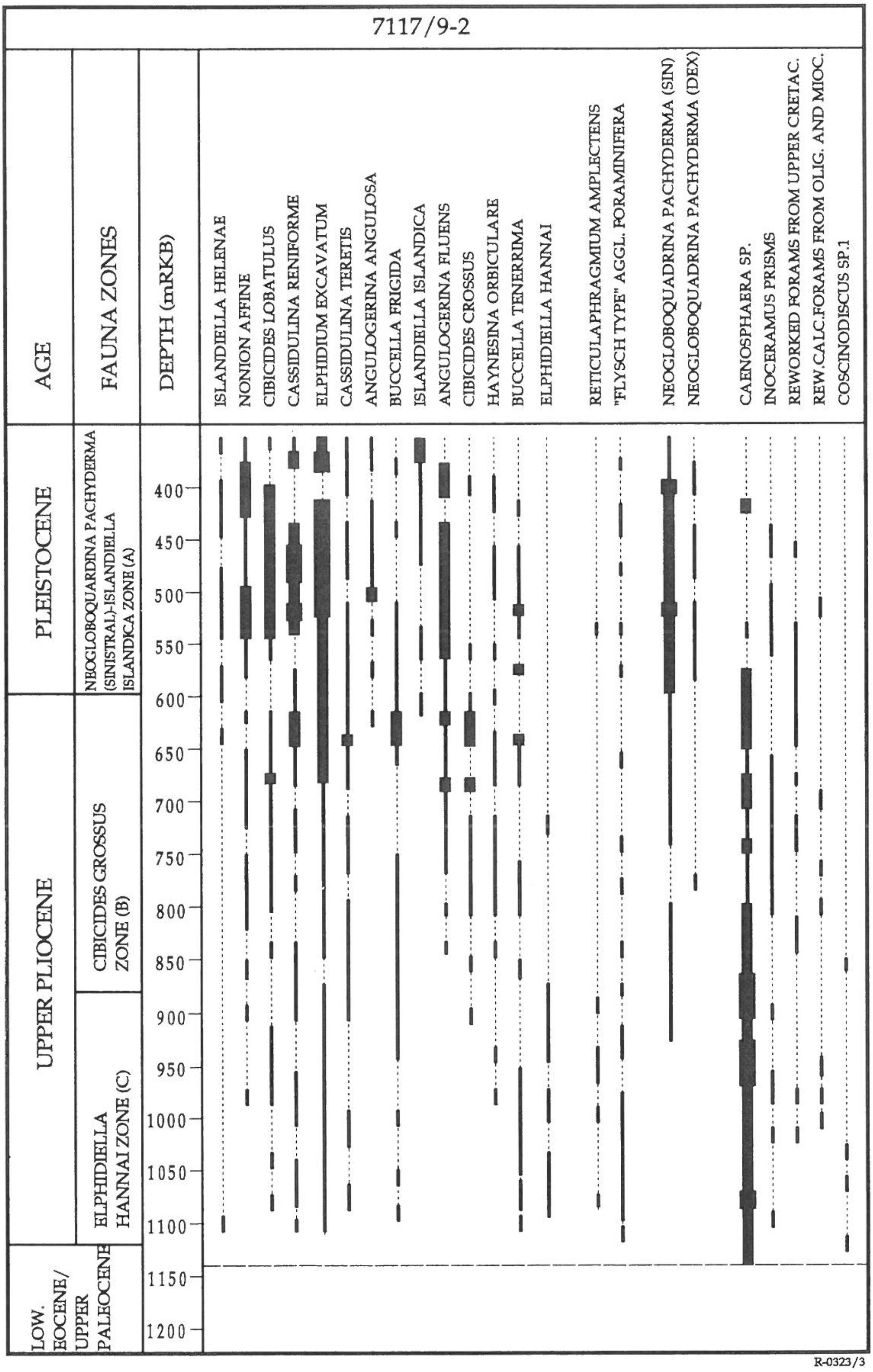


Fig. 10. Biostratigraphic range chart for Hole 7117/9-2.

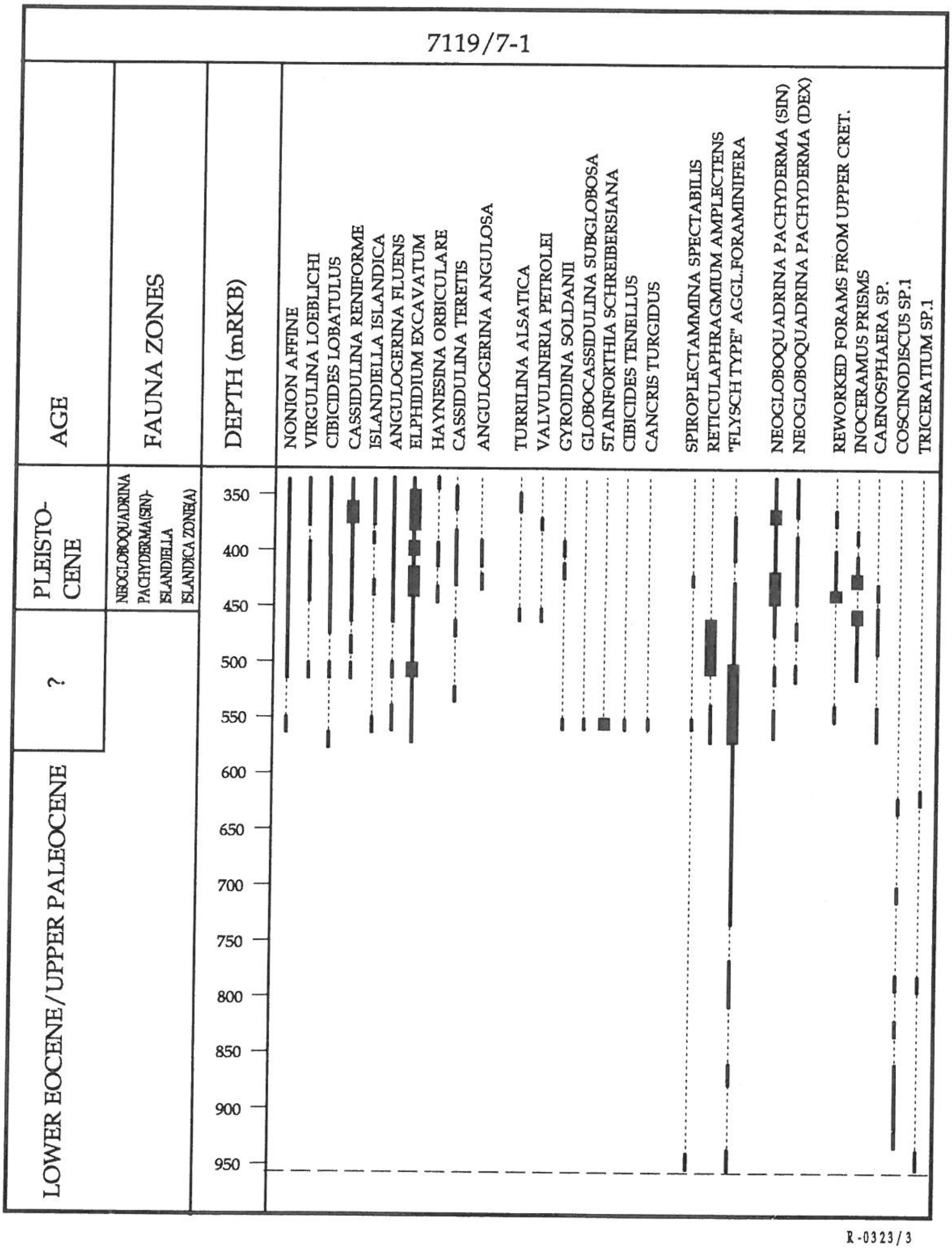
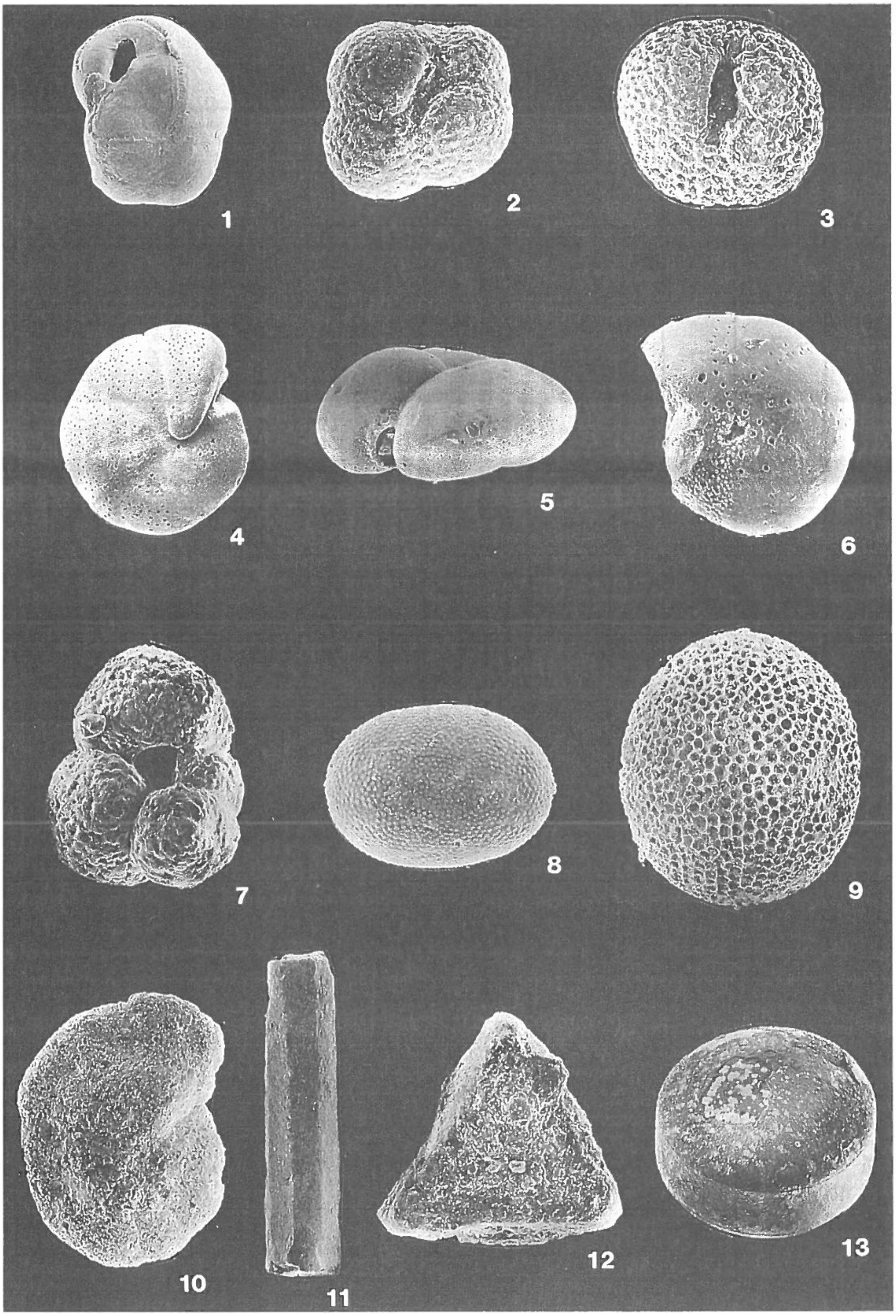


Fig. 11. Biostratigraphic range chart for Hole 7117/7-1.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lower/middle Eocene deposits in the North Sea. *Reticulophragmium amplectens* is found in lower/-middle Eocene deposits in the North Sea (King, 1989). The remaining agglutinated foraminifers are long ranging taxa of mainly lower Tertiary affinity. The agglutinated specimens are highly corroded and fragmented and we believe they were redeposited along with Eocene radiolarians of the genus *Caenosphaera* and a suite of foraminifer species ranging in age from Jurassic to Miocene.

The *C. grossus* Zone, as mentioned above, covers the same part of the sedimentary column in both holes. It also fits nicely in age below the overlying zone in both holes. From this evidence we conclude that it indicates a young, late Pliocene, age for the sediments. The uppermost part of the zone may represent the lowermost Pleistocene, based on the known time of extinction for *C. grossus*. Seismic data indicate a minor unconformity between faunal Zones A and B (Figs. 3, 6 and 7, Reflector 1) This is the Upper Regional Unconformity of Vorren et al. (1990).

Zone C: Elphidiella hannai *Zone*

Definition: Common occurrence of *E. hannai* (Figs. 9, 10 and 12).

The zone ranges from 900 to 1020 m in Hole 7117/9-1 and 880 to 1120 m in Hole 7117/9-2. It is found beneath Reflector 2 (Fig. 3). The occurrence of *E. hannai* is limited to this zone. In the North Sea *E. hannai* has a distribution range from the upper Pliocene to the lower Pleistocene (King, 1989). The same age is inferred from studies of Pliocene deposits from Arctic Canada, Alaska and Northern Greenland (Feyling-Hanssen, 1986). The remaining Plio-Pleistocene foraminifers are similar to those found in the overlying zones and consist of extant arctic and boreal species. *N. pachyderma* sin. is only found in a few scattered levels.

Our conclusion is that these foraminifers are in situ and do not represent downhole contamination due to the following arguments: *E. hannai* has not been found in any overlying sediment. The highest occurrence of this species is found at roughly the same sub-bottom depth in both holes. Above this zone a 20-inch casing which limits downfall, was placed. Should the fossils represent downfall, we should expect also to see *C. grossus* which is common in the overlying zone. This species is absent. Based on the occurrence of *E. hannai* we assign a late Pliocene age to this zone.

We find the same kinds of agglutinated foraminifers in this zone as in Zone B. Also here they are fragmented and wear signs of reworking. The common occurrence of early/middle Eocene radiolarians and late Cretaceous *Inoceramus* prisms as well as Cretaceous–Miocene benthic foraminifers represents redeposition from shelf erosion of Miocene, Paleogene and Mesozoic strata.

Zone D: Geoida *sp.*–Globigerina bulloides *Zone*

Definition: Common occurrence of *Geoida* sp. and *G. bulloides* (Figs. 9, 10 and 12).

The zone is only found in Hole 7117/9-1 and covers the interval 1020–1180 m. Seismically it corresponds to the sequence just above Reflector 3 which defines the lower boundary of fan deposits.

Geoida sp. (sponge spicule) is found in scattered samples also in other zones, but is here found commonly. In the North Sea and mid-Norwegian continental shelf this species is found throughout most of the Tertiary. The planktonic foraminifer *G. bulloides* is found today along the Norwegian margin further south. In Pliocene deposits drilled by ODP Leg 104 from the Vøring Plateau there is a strong dominance of this species together with *Neogloboquadrina atlantica* before 2.3 Ma (Spiegler and Jansen, 1990). Throughout the last 2.3 Ma *G. bulloides* is only rarely found in the warmest interglacials of the last 1 Ma, i.e. corresponing to Zone

Fig. 12. Scanning micrographs documenting the main index fossils. 1. *Islandiellea islandica*, × 133, 7117/9-1, 560 m; 2. *Neogloboquadrina pachyderma* (sinistral), × 233 7117/9-1, 450 m; 3. *Neogloboquadrina pachyderma* (sinistral), ("Encrusted" form), × 233, 7117/9-1, 450 m; 4. *Cibicides grossus*, × 100, 7117/9-1, 660 m; 5. *Cibicides grossus*, × 100, 7117/9-1, 660 m; 6. *Elphidiella hannai*, × 133, 7117/9-2, 1070 m; 7. *Globigerina bulloides*, × 233, 7117/9-1,1080 m; 8. *Geodia* sp., × 333, 7117/9-1, 1110 m; 9. *Cenosphaera* sp., × 233, 7117/9-1, 900 m; 10. *Cyclammina amplectens*, × 100, 7117/9-2, 1180 m; 11. *Inoceramus* prism, × 67, 7117/9-1, 900 m; 12. *Triceratium* sp., × 333, 7117/9-1, 910 m; 13. *Coscinodiscus* sp. 1 (Bettenstaedt et al., 1992), × 100, 7117/9-1, 885 m.

A. Thus, common occurrence of this species at high latitudes, probably relates to its maximum abundance zone defined at the Vøring Plateau south of the Bjørnøyrenna Fan (Fig. 1). We did not find *N. atlantica* associated with *G. bulloides* which is the case on the Vøring Plateau. Data from the mid-Norwegian Shelf landward of the Vøring Plateau (Eidvin and Riis, 1991) and from the northern North Sea (Eidvin and Riis, 1992) indicate, however, that there is a tendency of *N. atlantica* to stay away from more coastal areas in the Pliocene. We believe that this explains the absence of *N. atlantica* from coeval sediments from the Barents Sea holes. Based on this correlation, Zone D must be older than 2.3 Ma. A maxiumum abundance zone of *G. bulloides* is also described in North-Atlantic records from DSDP Leg 94 (Weaver and Clement, 1987), and was assigned an age of 2.4–2.1 Ma based on paleomagnetic data. The onset of strong *G. bulloides* occurrence took place in the lower normal polarity interval in the Gilbert Chron at about 4.4 Ma on the Vøring Plateau (Jansen and Spiegler, 1990; Bleil, 1990). This gives a maxium age of early Pliocene for Zone D. Based on sedimentological evidence (see below) we prefer to correlate Zone D to the upper part of the 4.4 to 2.3 Ma interval of high *G. bulloides* content in the Vøring Plateau record. This is now supported by new Ar/Ar data on volcaniclastics in sediments below the fan west of Bjørnøya, dating pre-fan sediments at 2.2–2.35 Ma (Mørk et al., 1993).

Our conclusion is therefore that the zone contains sediments of Pliocene age, probably slightly older than 2.3 Ma. The same mixed assemblage of Mesozoic, Paleogene and Miocene microfossils we found in the upper zones is also represented here. They are believed to be redeposited as a result of the erosion which led to the formation of the fan.

Below Zone D in Hole 7117/9-1 we record a microfossil fauna entirely consisting of agglutinated foraminifers and reticulate radiolarians (*Caenospaera* sp.). In contrast to the overlying zones they are not worn and fragmented, but appear fresh. No appearance of younger fossils is observed. The presence of *Reticulophragmium amplectens* and *Caenospaera* sp. indicates that these are lower/middle Eocene sediments correlatable to faunal Zones NSA 4 and NSP 6 in the North Sea zonation (King, 1989). Since these fossils are unfragmented and do not appear worn, and the sediments contain no mentionable amounts of younger fossils, we conclude that the sediments below Zone D are in situ Eocene deposits.

Below Zone C in Hole 7117/9-2 we observe a pure diatom microfossil flora with pyritized specimens. Among these we find *Coscinodiscus* sp. 1 (Bettenstedt et al., 1962) which indicates upper Paleocene–lower Eocene sediments. This corresponds to faunal Zone NSP 4 in the North Sea (King, 1989). We conclude that these sediments also are in situ Eocene deposits.

Based on the total absence of younger sediments and the common presence of Paleogene microfossils we propose that the lower zones of the wedge are directly underlain by in situ late Paleocene to middle Eocene deposits in the two holes on the Senja Ridge.

Hole 7119/7-1

This hole was drilled eastward of the Fan (Fig. 1) and contains a different biostratigraphic sequence than the two other holes to the west (Fig. 11).

360–460 m: The upper sedimentary section has a nearly identical fossil assemblage as Zone A in the two other holes and contains common *N. pachyderma* sin. (both encrusted and non-encrusted varieties). Dextrally coiling *N. pachyderma* is rare. Scattered late Cretaceous foraminifers are present.

460–590 m: This section contains a highly mixed assemblage. Agglutinated foraminifers such as *Reticulophragmium amplectens* and reticulate radiolarians indicating an early/middle Eocene age (King, 1989) predominate. Scattered Plio-Pleistocene foraminifers are also found. In addition to these, rare Oligocene–Miocene foraminifers occur in higher abundance than in the overlying interval. There is a lithologic boundary at 460 m in this hole. Above this level, distinct unconsolidated sediments are observed, while below are consolidated mudstones and scattered limestone layers. It is possible that the consolidated sediments are Eocene in age, and that the younger fossils represent downfall. No distinct zonation markers are found in the unit. It is also possible that some material was deposited by slides. A fault which may have caused such disturbance crosses the unit at about 0.7 s (Fig. 8).

590–885 m: This section is very fossil poor, and contains scattered agglutinated foraminifers and pyritized diatoms of the genus *Coscinodiscus* sp. According to King (1989) faunal Zones NSB 2 and NSP 4 from the North Sea are characterized by co-occurring diatoms of the genus *Coscinodiscus* sp. 1 and sp. 2 (Bettenstedt et al., 1962), representing the late Paleocene–early Eocene. We use this as the best age assignment for this sequence in the Barents Sea.

885–950 m: The section contains common *Coscinodiscus* sp. 1 which places the sediments in the late Paleocene–early Eocene (King, 1989).

Sediments corresponding to Zones B, C and D which define the Bjørnøyrenna Fan sequence are missing from this hole, as was also evident in the seismic record, documenting that fan sedimentation was limited to the areas west of this location.

Biostratigraphic conclusions

Previous studies of these sediment sections concluded that the sediments covering Zones B, C and D were in-situ Eocene–Miocene sediments. Younger fossils were considered to represent downfall, and the older considered redeposited in the Eocene (unpubl. industry reports). Spencer et al. (1984) contend that the section containing Zones B, C and D in Hole 7117/9-1 is of Oligocene to Pliocene age. Our biostratigraphic study indicates that these conclusions most likely are wrong, and that the whole fan sequence is younger, due to the following reasons:

(1) There is a well defined zonation of Plio-Pleistocene assemblages in both holes. The zonation represents a reasonable chronological succession which can be correlated to the mid-Norwegian Shelf and the North Sea. The boundaries between the zones are found at similar depths in both holes, making downhole contamination an unlikely reason for the appearance of young microfossils. The zonal boundaries correspond to marked reflector horizons (Fig. 3).

(2) The upper occurrence of the Pliocene foraminifer *E. hannai* is found at large sediment depth. Above this depth a 20-inch casing was mounted, thus making it highly unlikely that the reason it was found so deep originates from downfall. The likely reason is that the sediments are late Pliocene in age, documenting extremely high Plio-Pleistocene sedimentation rates.

(3) Surface textures of fossils older than the Plio-Pleistocene show clear signs of redeposition.

(4) In the sediments below the assemblage zones, i.e. below the fan, we find no Plio-Pleistocene fossils, indicating that downhole contamination is a minor problem. Redeposition of Jurassic–Paleogene microfossils higher in the section was probably very common due to the erosive processes that formed the fans.

(5) Recent Ar/Ar data on volcaniclastic debris in sediments below the fan in the area west of Bjørnøya, give ages of 2.20–2.35 ± 0.12 Ma (Mørk et al., 1993), thereby confirming our conclusion of a young (late Pliocene and younger) age for the formation of the fans.

Strontium isotope results

Strontium isotope analyses of calcareous material (mollusc fragments) were performed at selected levels in holes 7117/9-1 and -2 (Fig. 13). Age information from the $^{87}Sr/^{86}Sr$-ratio can be gained by comparison to global strontium isotope curves (Palmer and Elderfield, 1985; DePaolo and Ingram, 1985; Koepnick et al., 1985; DePaolo, 1986; Hess et al., 1986). The results are shown in Fig. 13 and Table 1, and document the spread in ages we expect from the mixed microfossil assemblages which includes both autochtonous and allochtonous fossils, thus the age information from the Sr-isotope analyses is not conclusive. However, viewed in the context of the erosive processes responsible for the fan formation, they may be taken as support for our age inference. The main result is that material interpreted to be in-situ Plio-Pleistocene shows systematic changes in age which supports the age interpretation based on the biostratigraphic zones. These are the younger ages given in Fig. 13. Material from Zone C gives late

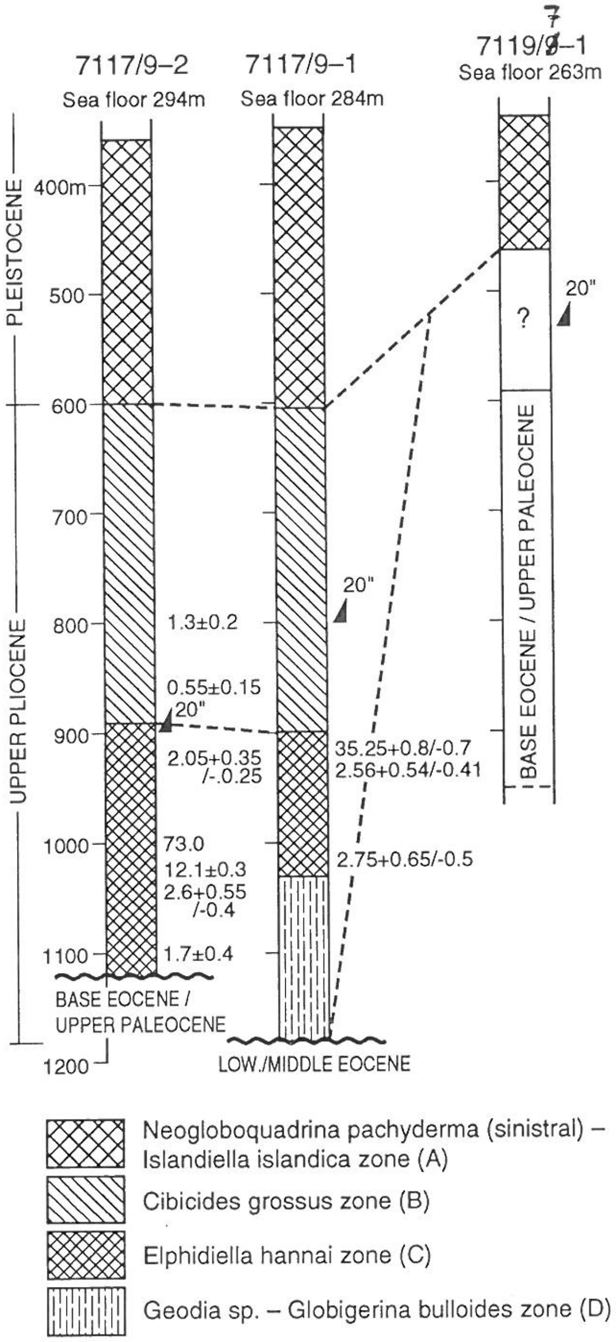

Fig. 13. Correlation of faunal zones between the holes studied. Also shown is the relationship between faunal zones and Sr ages and the position of the 20-inch casing.

Pliocene ages (2.05–2.75 Ma). The Sr age of material from Zone B is somewhat younger than the biostratigraphic determined age (Samples Sr 1 and Sr 2, Table 1). This discrepancy may be due to the inaccuracy of the Sr-method or downfall.

TABLE 1

Strontium isotope analyses of the mollusc fragments

Sample	Depth (m RKB)	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ (normalised)	Date (Ma)	Uncertainty (Ma)
Hole 7117/9-1					
Sr 1	800	0.709021	0.709005	1.30	+0.2/−0.2
Sr 2	860	0.709054	0.709038	0.55	+0.15/−0.15
Sr 3	940	0.708996	0.708980	2.05	+0.35/−0.25
Sr 4	960	0.708611	0.708595	16.00	
Sr 5	1000	0.707633	0.707617	73.00	
Sr 6	1020	0.708786	0.708770	12.10	+0.3/−0.3
Sr 7	1040	0.708981	0.708965	2.60	+0.55/−0.4
Sr 8	1100	0.709007	0.708991	1.70	+0.4/−0.4
Hole 7117/9-2					
Sr 9	810	0.707314	0.707298	109, 117, 140	
Sr 10	920	0.707809	0.707793	35.25	+0.8/−0.7
Sr 11	945	0.708942	0.708966	2.56	+0.54/−0.41
Sr 12	1015	0.708978	0.708962	2.75	+0.65/−0.5
Sr 13	1115	0.707501	0.707485	80, Jur. Perm.	

Paleoenvironmental indicators

The presence of planktonic foraminifers in near-coast/shelf regions indicates open marine environments, high salinity and absence of low salinity coastal waters. Planktonic foraminifers are common in the upper Zone D and in Zone A, indicating relatively deep waters under the deposition of these zones. *E. hannai* is by many workers believed to be a shallow-water indicator (Feyling-Hanssen, 1986; Skarbø and Verdenius, 1986; King, 1989), indicating rather shallow water during the formation of Zone C. Some influx of planktonic foraminifers and the deeper dwelling *C. grossus* (Feyling-Hanssen, 1986; Skarbø and Verdenius, 1986; King, 1989) in Zone B indicates that the water depth increased again after the deposition of Zone C.

Ice rafted material

The sediments recovered from Zones A–D consist mainly of unconsolidated material. Common to them is the frequent presence of gravel sized

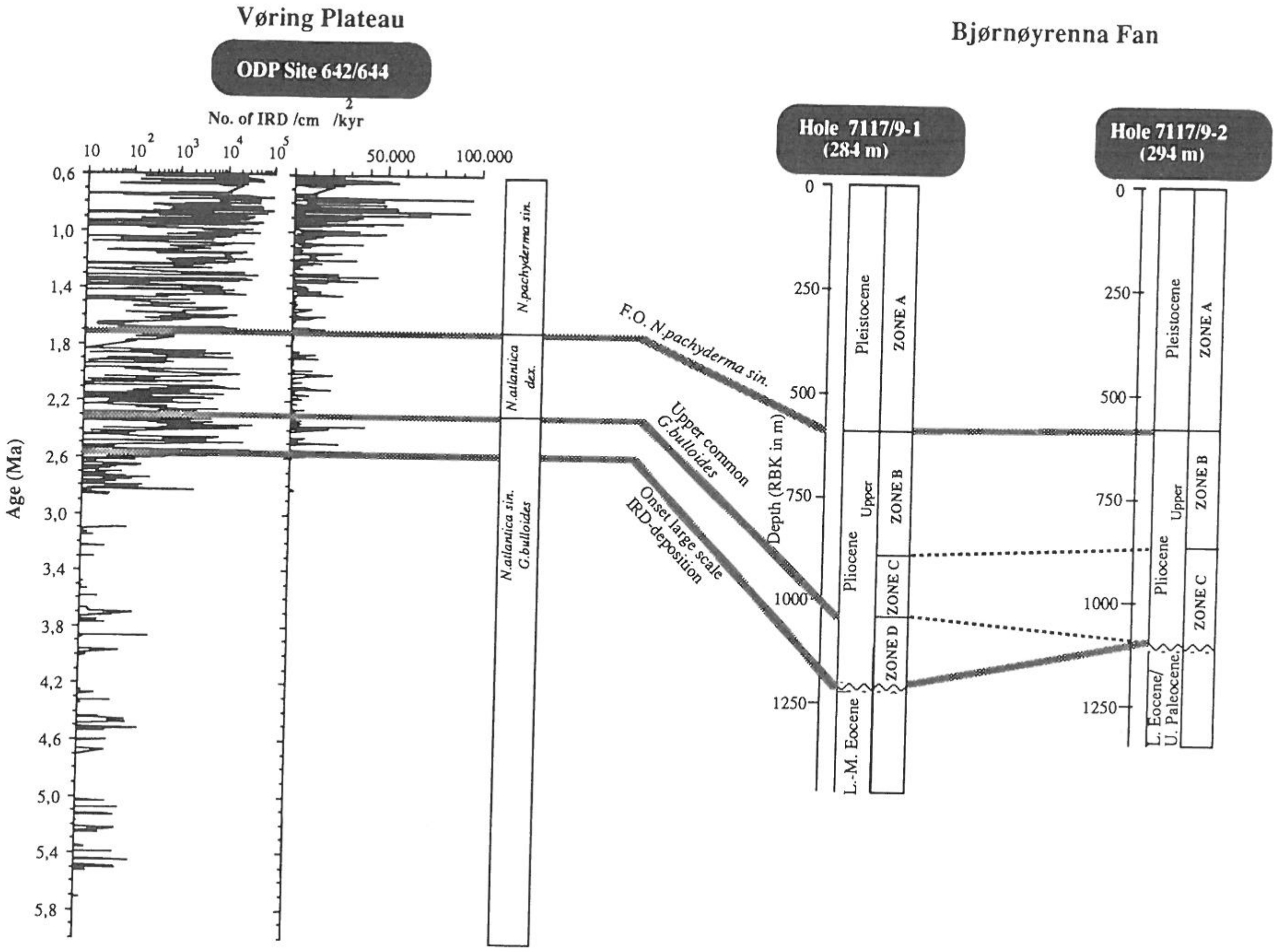

Fig. 15. Correlation of Vøring Plateau ODP sites (Jansen and Sjøholm, 1991) and Barents Sea stratigraphy.

1991). Small fluxes of IRD are recorded in sediments as old as 5.5 Ma. The fluxes were small until 2.56 Ma, when IRD-deposition increased by several orders of magnitude, signalling the time when large ice sheets formed in Scandinavia, being able to spread large quantities of calving ice-bergs over the ocean (Jansen et al., 1990; Jansen and Sjøholm, 1991). It is likely that the ice-derived material of the fans was deposited in conjunction with this phase of enhanced glaciation and thus postdates approximately 2.6 Ma. This corresponds well with the above contention that Zones D–A are of late Pliocene and younger age and the correlation of the Vøring Plateau biostratigraphy with the holes investigated in this study. We illustrate this relationship in Fig. 15.

DSDP Site 344 drilled during Leg 38 of DSDP is located east of the Knipovitch Ridge in the distal portions of the Storfjord Fan (Fig. 1). A sill, probably near basement, is dated at 3 Ma by potassium/argon (Talwani et al., 1976). The sediment column contains mixtures of turbidites and glaciomarine sediments, and biostratigraphic analyses of the sequence (Talwani et al., 1976) interpreted in view of the Leg 104 biostratigraphy indicate that the whole sequence postdates the Miocene/Pliocene boundary. This indicates a young age also for the Storfjord Fan.

Oxygen isotope records which reflect the late Tertiary cooling and the onset of large scale Northern Hemisphere glaciation document a series of glacial phases superimposed on a cooling trend in the period 3.5–2.3 Ma (Shackleton et al., 1984; Keigwin, 1987; Raymo et al., 1989; Sarnthein and Thiedemann, 1992; Jansen et al., in press). While the onset of large scale IRD-deposition appears rock fragments. These are angular to sub-angular, a majority of these fragments consists of sedimentary rocks typical for the Barents Shelf, while a significant contribution comes from crystalline rock fragments (see example in Fig. 14). The significant presence of sub-angular gravel is interpreted to result from ice-transport either as ice-rafted material (IRD) or directly deposited by ice-sheets.

ODP Leg 104 holes from the Vøring Plateau provide a nearly continuous record of IRD-deposition over the last six million years in the eastern Norwgeian Sea (Fig. 15; Jansen and Sjøholm,

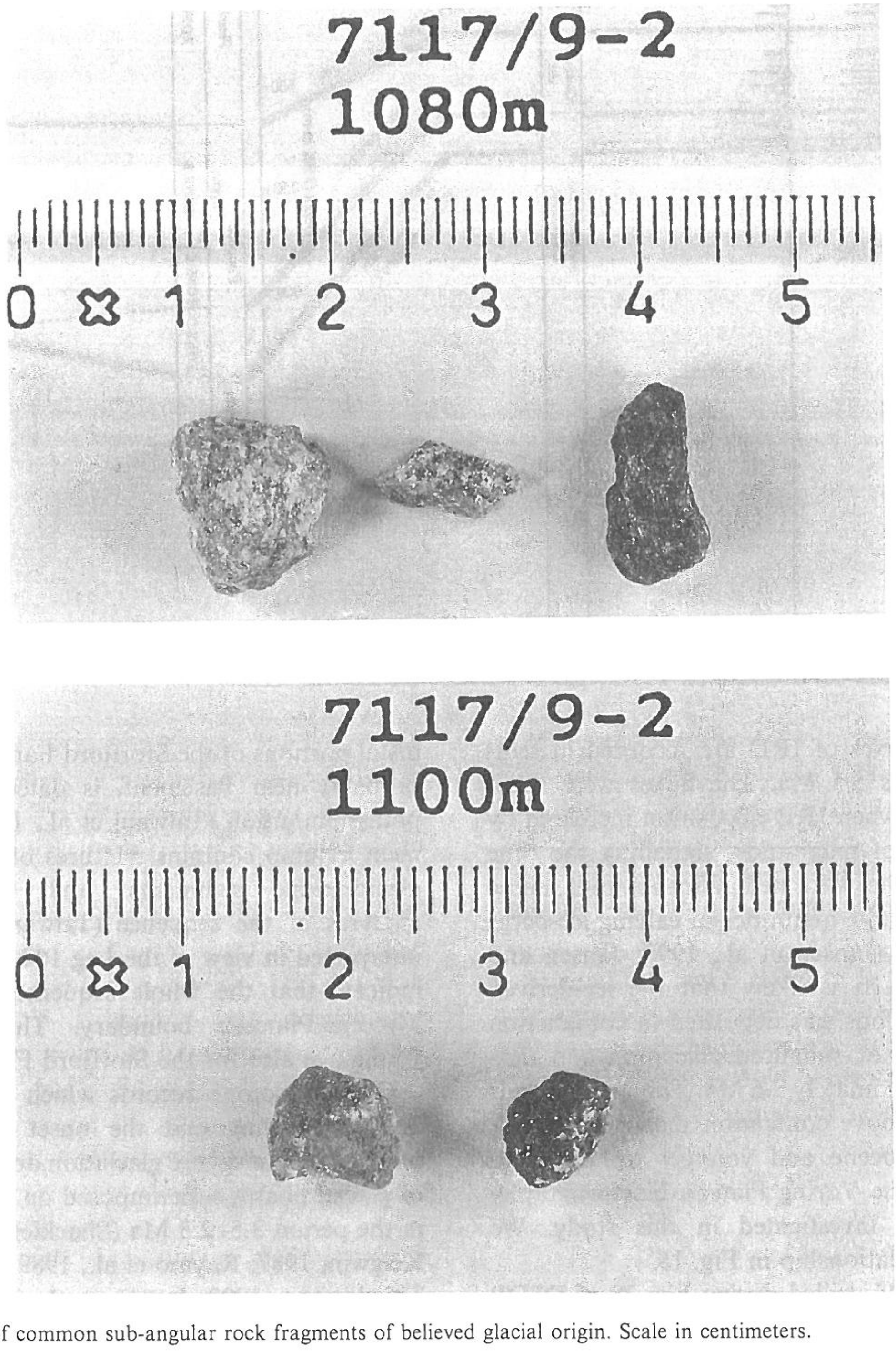

Fig. 14. Pictures of common sub-angular rock fragments of believed glacial origin. Scale in centimeters.

like a sudden step (Fig. 15), the oxygen isotope records indicate a trend toward stronger glaciation during this period. Commencement of glacial erosion and deposition on the Barents Shelf most likely happened as a part of this evolution. The signs of IRD on the Vøring Plateau in the Messinian at 5.5 Ma probably represents a maximum age for the deposition of glacial debris off the Barents Shelf. The low flux before 2.56 Ma indicates, however, that significant glacial erosion on the shelf areas off northern Europe commenced after this time. Hence, the time when glacial processes were intense enough to build large fans probably was after 2.6 Ma. An intensification of glaciation and a shift to dominant 100-kyr cyclicity in ice-volume fluctuations took place after 1 Ma. This is clearly documented by the increased IRD-flux shown in Fig. 15, and in oxygen isotope records (Shackleton et al., 1984; Raymo et al., 1989; Ruddiman et al., 1989). It is likely that this also marked an intensification of glacial erosion in the Barents Sea. We suggest that this period corresponds to the sequence deposited during most of Zone A in the Bjørnøyrenna Fan. Since the zone is bounded by a lower unconformity according to seismic data, it is not clear how long the period represented by the zone really is. The biostratigraphic resolution is also not sufficient to accurately date the base of Zone A.

Discussion

Trough mouth fans of variable sizes are found off a number of formerly glaciated shelves both off the North Sea, off Greenland, off Spitzbergen, in the Arctic Ocean and in Antarctica, in addition to the ones off the Barents Sea. It appears that particularly active sediment transport takes place in shelf areas with localized troughs. While it is uncontroversial that the fans partly are formed due to glacial erosion and deposition, the onset of fan build-up and the time needed to produce them is more problematic to assess.

The young age for the Bjørnøyrenna Fan advocated for in this paper indicates that glaciation on shelves is a highly active erosion agent, capable of retransporting vast sediment quantities. A number of processes probably interacted to produce this result: direct glacial erosion by ice-sheets based in the Barents Sea. Most of the Barents Sea was ice covered during the last glacial maximum (Vorren et al., 1989, 1990; Elverhøi et al., 1988), and we presume this was the case also in a number of earlier glaciations. The deep erosional channels related to the base of the wedge in the Bjørnøya area (Sættem et al., 1992) indicate that the ice margin was located very close to these localities as early as the late Pliocene. Given the 2.6 Ma age for the onset of repeated strong glaciations in Scandinavia (Jansen et al., 1990; Jansen and Sjøholm, 1991) it is likely that the shelf was covered by ice during a major part of this period. The rapid shifts of regressions/transgressions due to the combination of glacio-eustatic sea-level variations and glacio-isostatic compensation also contributed to sediment removal and redistribution.

The high rates of erosion in the Barents Sea, particularly in the late Pliocene, may possibly be related to a topography different from the present one. Purely theoretical considerations indicate that the isostatic effect of removing a sheet of 1000 m of sediments with a density slightly above 2 g/cm^3, will be a lowering of the surface of approximately 500–600 m (Riis and Fjeldskaar, in press; Vågnes and Faleide, in press). Thus, the Barents Sea may have been elevated above sea level prior to the onset of the Pliocene erosion phase.

From bore-holes it is also known that the Stappen High in the Barents Sea and the Svalbard orogenic belt were strongly affected by tectonic movement, mainly in Eocene times (Gabrielsen et al., 1990; Wood et al., 1990). Compression tectonics probably related to this phase is described from the northern Barents Sea (Gabrielsen et al., 1990). We suggest that these tectonic movements caused uplift which preconditioned the area for glaciation due to the increased altitude.

This suggests that in the northwestern and northern parts of the Barents Sea, much of the observed erosion can be related to Paleogene tectonic uplift, while in the central Barents Sea, Tertiary tectonic effects were weak. Here, the main erosion can be related to glacial processes, and the uplift can be interpreted mainly as an isostatic compensation to the erosion.

The Barents Sea stratigraphy contains excellent source rocks and reservoirs for hydrocarbons. So far, however, prospecting has resulted only in a limited number of gas discoveries. In most prospects, residual oil is abundant, while significant quantities of movable oil are reported from one field only (Snøhvit). Apparently none of the discovered fields are filled to the spill point. It can be argued that the hydrocarbon traps were affected by intense Neogene erosion in a number of ways, causing leakage and redistribution of gas and oil (Skagen, 1993; Riis, in press). The most important effect is suggested to be the cooling related to the removal of overburden which stopped hydrocarbon generation in mature Triassic and Jurassic source rocks in the large platform areas of the Barents Sea. Thus, in most of the traps, no gas was being created to replace the gas that was leaking out of the traps during the last 1–2 million years.

Acknowledgements

Special thanks are due to O. Skarbø for sharing results and to S. Olafsen, B. Ruus, R. Williams and J. Ellingsen for technical assistance. We also thank K.R. Bjørklund, P. Blystad, W. Fjeldskaar, D. Helliksen, E. Mearns, F. Moe, Aa. Moe and P. van Veen for contributing in different ways to this study. GECO is thanked for providing seismic lines.

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Paper 6:
The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area)

The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area)

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Eidvin, T., Goll, R. M., Grogan, P., Smelror, M. & Ulleberg, K.: The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area). *Norsk Geologisk Tidsskrift*, Vol. 78, pp. 99–123. Oslo 1998. ISSN 0029-196X.

Pleistocene to Eocene stratigraphy and geological evolution of the thick Cenozoic fan deposits on the western Barents Sea continental margin SW of Bjørnøya are interpreted on the basis of seismic data and the results of biostratigraphic analysis (foraminifera, dinoflagellate cysts and radiolaria) from exploration well 7316/5-1. Strontium isotope ages are also obtained from three levels. The biostratigraphic analysis reveals seven informal zones based on foraminifera, four informal zones based on dinoflagellates, and five zones based on radiolaria fauna. Glacially derived Upper Pliocene and Pleistocene sediments rest unconformably on a Lower Oligocene to Lower Miocene section. An unconformity between the Lower Oligocene and Middle Eocene is also recorded. Prior to this investigation Oligocene sediments had not been encountered in exploration wells in the Barents Sea. The Oligocene benthonic foraminiferal fauna found in well 7316/5-1 is very similar to the fauna recorded in outcrop at Forlandsundet. Strontium-isotope correlation suggests, however, that the Oligocene section found in the Barents Sea is 5–6 m.y. older than that found at Forlandsundet.

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1. Introduction

Well 7316/5-1 is located in the southwestern part (73°31'N, 16°26'E) of the Vestbakken volcanic province (Fig. 1), and was the first well drilled to test the hydrocarbon potential of the clastic deposits in the Tertiary basins of the western Barents Shelf. The well is also the northwestern-most exploration well drilled on the Norwegian continental shelf to date. The well was drilled by Norsk Hydro a.s. on behalf of the PL 184 licence, which has now been relinquished. In order to assure that the results reported here are consistent with electric logs and other technical information concerning this well, all depths at this site are expressed as metres below the rig floor (m RKB) throughout the remainder of this paper. Therefore, 477 m must be subtracted from m RKB in order to convert these depths to metres below the sea floor. The well was drilled to a total depth of 4027 m RKB and is classified as a gas discovery after encountering a 18 m gas column in Middle Eocene sandstones at 1340 m RKB.

The Cenozoic succession of the western Barents Shelf is the result of several phases of extensive erosion and redeposition, and its stratigraphic interpretation has not been straightforward. Based on varying age determinations of the sequences, several different depositional history scenarios have been proposed for the Cenozoic basin development of this shelf margin area (Spencer et al. 1984; Nøttvedt et al. 1988; Vorren et al. 1991; Eidvin et al. 1993; Sættem et al. 1994). The objectives of the present study are to redate the upper part of well 7316/5-1 (i.e. the Pleistocene to Middle Eocene succession between 567 and 1600 m) by means of foraminifera, dinoflagellates, radiolaria and strontium-isotope analysis. We have also correlated the well stratigraphy to the seismic, and this provides the basis for a stratigraphic and regional geological model for the PL 184 licence and adjacent areas.

Previous studies of particular relevance to our work include the redating of the Palaeogene and Neogene sequences in wells 7117/9-1 and 7117/9-2 on the Senja Ridge, and of 7119/7-1 in the Tromsø Basin (Eidvin et al. 1993), together with the study of shallow cores which recovered Upper Palaeocene, Middle Eocene, Lower Miocene and Upper Pliocene–Pleistocene strata in the Bjørnøya West area (Sættem et al. 1994, Mørk & Duncan 1993) (Figs. 1, 2). Recent biostratigraphic information and paleomagnetic datings from the Ocean Drilling Program Leg 104 on the Vøring Plateau in the Norwegian Sea, provide further relevant information used to interpret and calibrate the stratigraphic data obtained from the micropalaeontology and palynology of well 7316/5-1. There are few earlier papers on Cenozoic foraminifera and dinoflagellates from the Barents Shelf area. Oligocene benthonic foraminifera have been described from Forlandsundet on Spitsbergen (Fig. 2) by Feyling-Hanssen & Ulleberg (1984), while Palaeogene dinoflagellates have been documented from Spitsbergen by Manum (1960), Head (1984, 1989) and Manum &

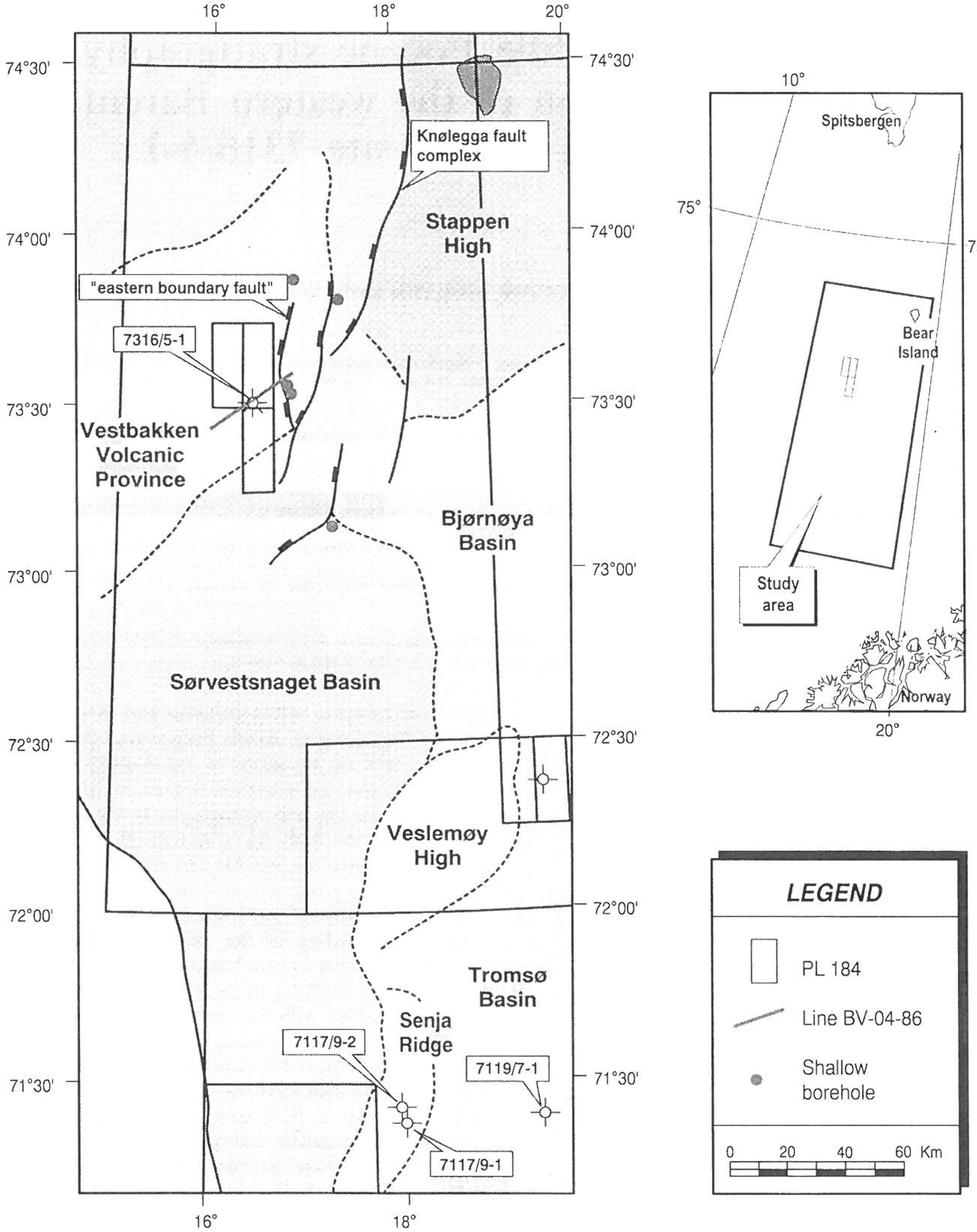

Fig. 1. Location of the regional seismic line NPD BV-04-86 and well 7316/5-1. Main structural features and location of other wells and shallow boreholes referred in the text are also shown.

Throndsen (1986). In the present study strontium-isotope analyses are carried out on tests of benthonic calcareous foraminifera from the Forlandsundet section, and some of the samples are re-examined for dinoflagellates.

This paper is an updated and revised version of the contribution by Eidvin et al. (1994). All absolute ages are based on Berggren et al. (1985) if not stated otherwise.

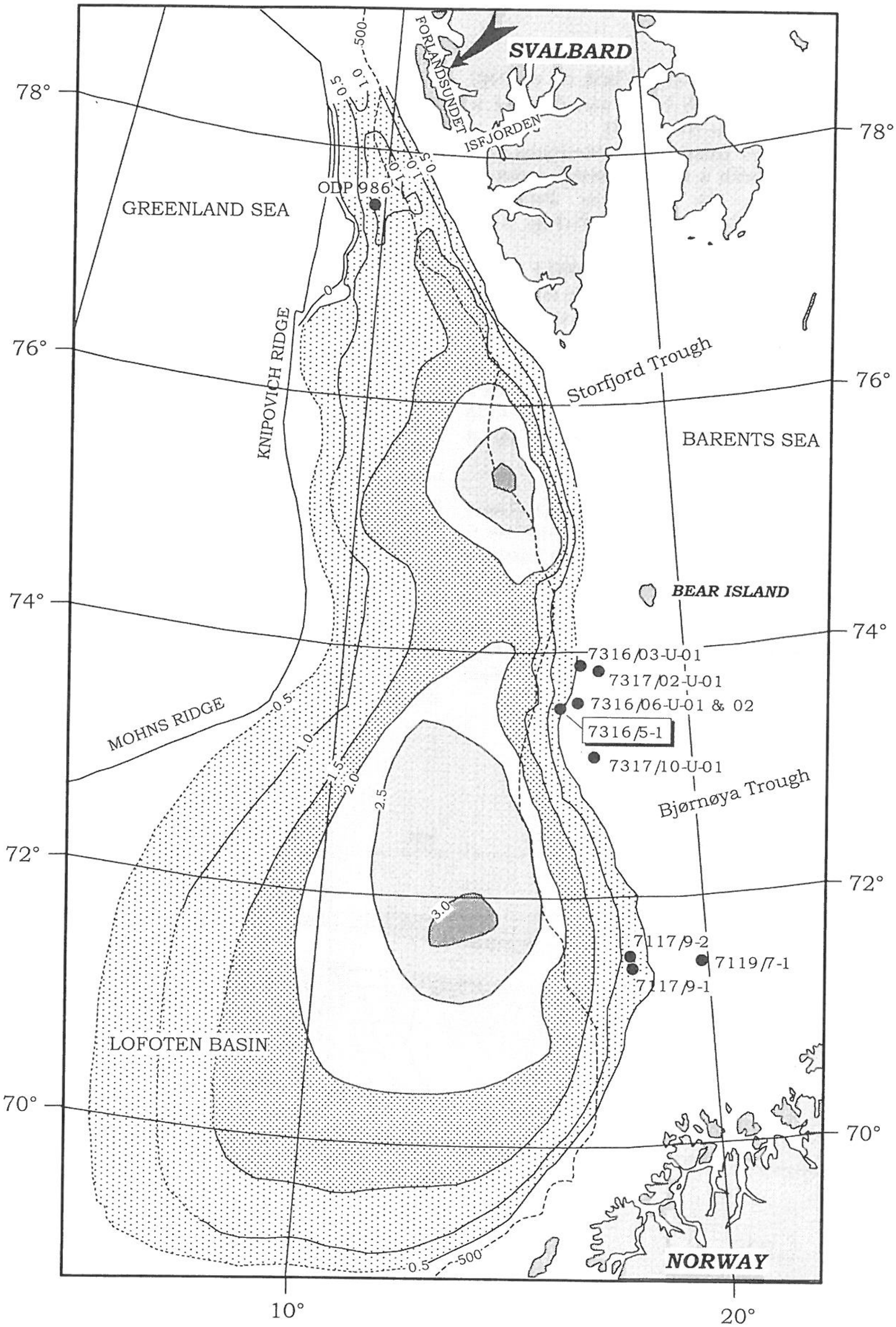

Fig. 2. Location of well 7316/5-1 and wells, shallow boreholes and ODP-borehole referred to in the text. The map is an isopach map of the glacial sediments along the western Barents Sea-Svalbard continental margin. Contour interval 0.5 s twt (modified after Faleide et al. 1996).

2. The geological setting

2.1 Seismic interpretation

Well 7316/5-1 is drilled at shotpoint 2058 on the NE-oriented seismic line NPD BV-04-86, and this line is used to illustrate the well tie (Figs. 1, 2).

The description below compares the biostratigraphically defined intervals with a regional seismic interpretation performed by the Norwegian Petroleum Directorate prior to the drilling of the well (Figs. 3, 4).

Interval 477–948 m RKB (454–925 m MSL) (Pleistocene–Upper Pliocene). – The base of this interval at 1123 ms twt can be correlated to the intra-Upper Pliocene horizon (i.e. base 'clastic wedge') (Figs. 3, 4). The event represents a marked angular discordance, both east and west of the well site. The reflection has a variable amplitude, and is very weak and difficult to interpret towards the west. The horizon has a dip of ca. 1.5° to the west.

Interval 948–960 m RKB (925–937 m MSL) (Lower Miocene). – On the seismic this 12-m-thick interval is recorded between 1123 and 1134 ms twt. The reflection at the base of the interval is continuous and exhibits strong amplitude across the licence area. The event defines a marked syncline east of the well site towards the eastern boundary fault (Fig. 3). West and south of the well site the reflection is truncated by the base Pliocene unconformity.

The reflection representing the intra-Lower Miocene horizon (Fig. 3) appears to coincide with the lower sequence boundary of a thick unit (more than 350 ms, i.e. approximately 380 m at shotpoint 1670, Fig. 3). Miocene and possible Pliocene sediments are preserved in the syncline east of the well. In the upper part of the sequence there is a marked break (truncating the wedge east of the well) possibly corresponding to the Middle–Late Miocene interval. The lower part of the sequence exhibits a parallel reflection pattern. The upper part exhibits indications of progradation from the east.

Interval 960–982 m RKB (937–959 m MSL) (Lower Miocene–Lower Oligocene). – Based on biostratigraphic evidence, only a general Early Miocene–Early Oligocene age can be inferred for this sequence. The reflection described above may represent the intra Miocene or the base Miocene, but it may also be associated with a larger hiatus. The interval 960–982 m is above the intra Oligocene reflector, recognized at about 1180 ms (1009 m RKB, 986 m MSL) in 7316/5-1.

The lower part of the shallow borehole 7316/06-U-01 (to the east of 7316/5-1, Fig. 2) is dated as Early Miocene (Sættem et al. 1994). On the seismic profile it appears that these deposits are also located below the reflector described above. It appears, however, that the sequence penetrated in 7316/06-U-01 is either condensed or truncated by a hiatus in well 7316/5-1.

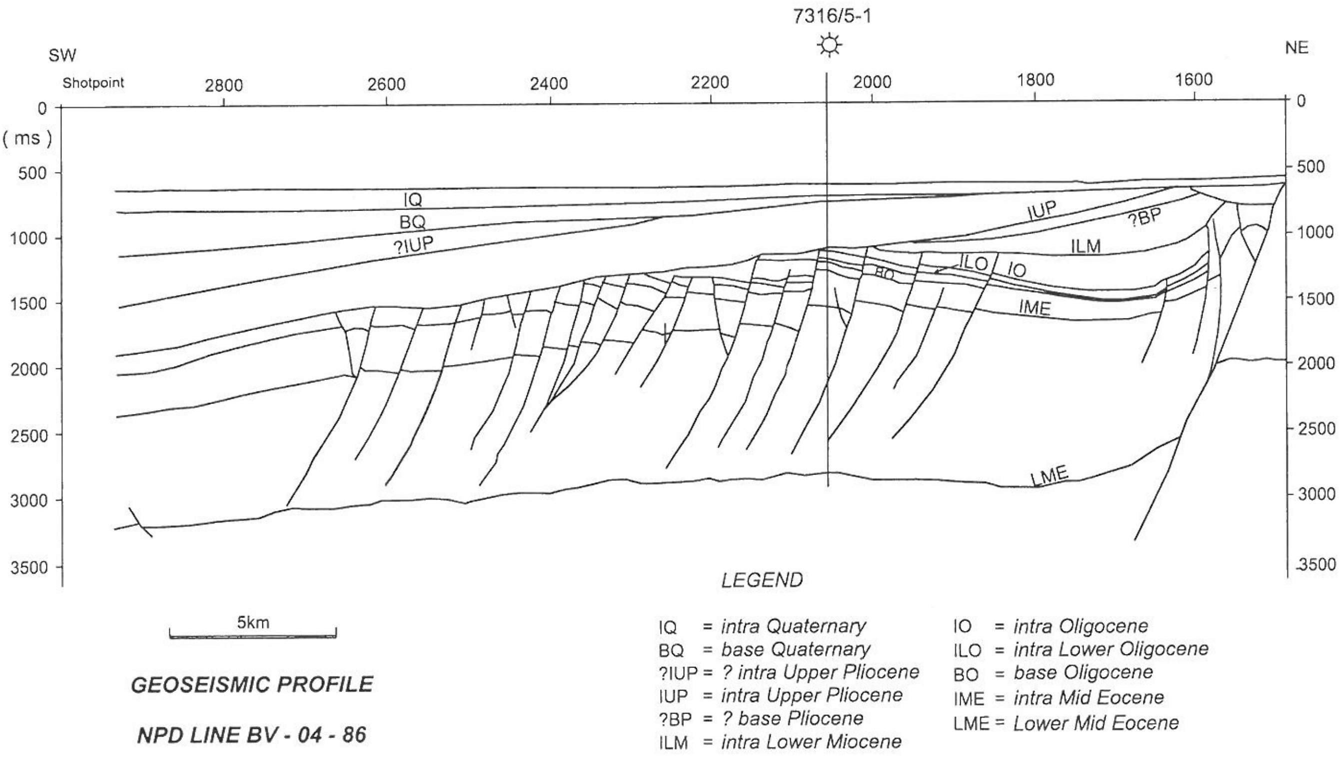

Fig. 3. Digitized seismic line NPD BV-04-86. Location in Fig. 1.

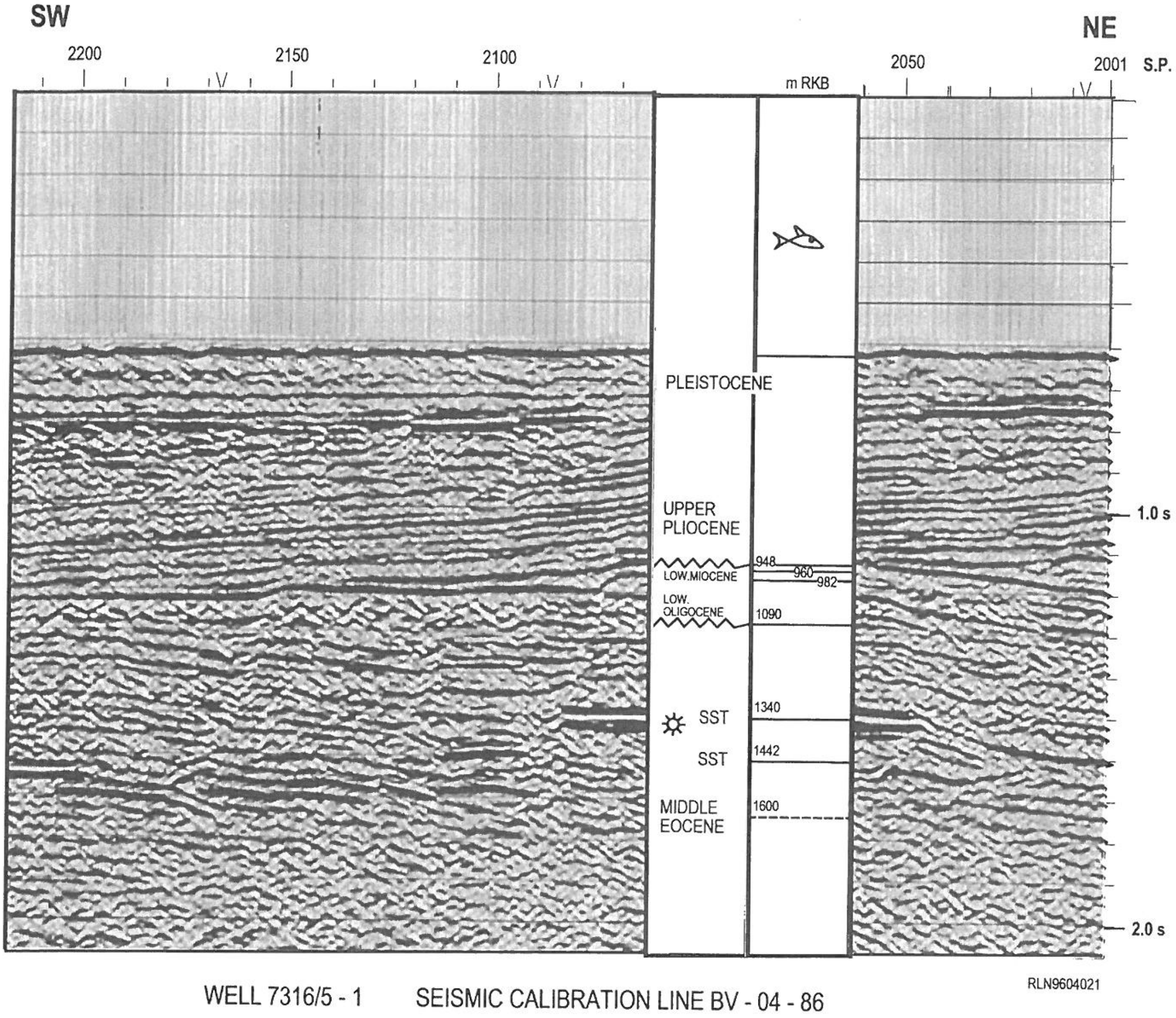

Fig. 4. Correlation between well and seismic profile.

East of 7316/5-1, the sequence thickens from about 50 ms to more than 250 ms twt (Fig. 3). The interval shows a transparent character with little indication of stratification, as might be expected for a sequence deposited in an outer shelf/slope environment (Sættem et al. 1994). The thinning of the sequence towards the well location is possibly due to condensing of the Lower Miocene–Upper Oligocene deposits.

Interval 982–1090 m RKB (959–1067 m MSL) (Lower Oligocene). – This interval occurs between 1154 and 1255 ms twt at the well site. The base of the sequence corresponds to the base Oligocene seismic marker (Fig. 3). In addition, there are two mapped seismic horizons within this interval, i.e. one weak intra Oligocene reflection picked at 1180 ms (1009 m RKB, 986 m MSL) and one strong, more continuous, intra Lower Oligocene reflector recognized at 1205 ms (1036 m RKB, 1013 m MSL).

The weak reflection picked at 1180 ms is better expressed further east and defines the base of the transparent interval described above. The stronger reflections at 1205 ms and 1255 ms which occur towards the base of the Lower Oligocene sequence appear as minor sequence boundaries, but both reflectors exhibit subtle truncation of underlying sequences. The Lower Oligocene unit appears to become thinner towards the eastern boundary fault (in contrast to the overlying sequences), but becomes gradually thicker to the west. West of the well site, parts of the Lower Oligocene unit are eroded and rest directly beneath the base Pliocene.

Interval 1090–1600 m RKB (1067–1577 m MSL) (Middle Eocene). – The interval between 1090 and 1600 m RKB (lowermost studied sample) corresponds to the seismic unit between 1255 and 1731 ms twt in the well. Upper Eocene deposits are not present in the well, and the upper boundary of this unit corresponds to a major unconformity. The reflector exhibits a marked truncation of older strata east of the well.

The Middle Eocene sequence exhibits almost parallel bedding, but with weaker amplitudes than the overlying Oligocene sequence. Towards the east the reflectivity appears somewhat stronger at some levels, but becomes very weak towards the west and also deeper than 1731 ms.

The upper sandy unit (top at 1492 ms twt) in the Middle Eocene sequence contains an 18 m gas column. This is accompanied by a marked increase in amplitude (bright spot) in the small rotated fault block penetrated by the well.

An intra-Middle Eocene horizon is recognised at 1550 ms twt (1392 m RKB, 1369 m MSL) between the two sandy units. An approximate correlation to the shallow drill site 7316/06-U-02 to the east (Sættem et al. 1994) (Fig. 2) indicates that the sediments recovered in the shallow core correlate to the sequence between 1400 and 1600 m RKB in 7316/5-1.

2.2 Lithology and lithostratigraphy of 7316/5-1

2.2.1 The Nordland Group (567–948 m RKB; 94–475 m below the sea floor)

This section has been observed in 29 sidewall cores, one conventional core (Core 1; 896-906.6 m RKB) and ditch cuttings below 887 m RKB (Figs. 5, 6). The interval consists of clay-rich diamicton interbedded with unconsolidated coarse- to medium-grained sand. The sand beds are 5–58 m thick, including a 52-m-thick unit at the base of the section. Structureless sand lacking laminations characterizes Core 1, which penetrated the upper portion of this basal unit. Subangular to angular pebbles and stones of both sedimentary and crystalline rocks occur throughout the core, both as distinct layers and dispersed intervals. The uppermost 20–25 cm of the core penetrated a large block of sedimentary rock. Crystalline pebbles interpreted as dropstones also occur in some of the sidewall cores. The clay-rich interbeds also contain significant concentrations of sand and pebbles.

The lithologies observed in this section are similar to the glaciomarine sediments of the Norwegian Sea. The sand units presumably accumulated during the sea-level lowstands associated with glacial stadia. The basal sand unit may be attributed to a glaciofluvial meltwater delta. The larger stones are interpreted as ice-rafted dropstones.

The glaciomarine sediments of the Vøring Plateau have been the subject of recent studies by Jansen (1991, 1993 and 1995) and Jansen & Sjøholm (1991), and the results of these investigations provide the best basis for inferring the age of the Nordland Group at 7316/5-1. There are traces of ice-dropped material in sediments as old as nearly 12 m.y. on the Vøring Plateau. The frequency of such ice-rafted material increases during the period of 6.5–5.5 Ma, which correlates with the Messinian Stage. The pronounced Messinian sea-level fall observed at many localities globally is attributed to an expansion of the Antarctic ice cap. The frequency of ice-dropped material remains relatively low between 5.5 Ma and 2.6 Ma, but the great increase in the supply of ice-dropped material after about 2.6 Ma reflects the marked expansion of northern European glaciers. This latter age is taken as the maximum age of the Nordland Formation at 7316/5-1.

2.2.2 The Sotbakken Group (948–1600 m RKB (lowest sample analysed); 475–1127 m below sea floor)

The upper part of this interval (i.e. 948–1090 m) comprises a bedrock sequence not previously encountered in other exploration wells in the western Barents Sea. However, in the absence of an alternative established lithostratigraphic name these sediments are assigned to the Sotbakken Group of Dalland et al. (1988).

The Sotbakken Group has been sampled by five sidewall cores (948–1022 m RKB), two conventional cores (Core 2; 1347.5-1374.4 m RKB, and Core 3; 1460.5–1472 m RKB) and ditch cuttings at 2–20 m intervals (Figs. 5, 6). The petrophysical logs support the lithological interpretation. The section consists primarily of claystone, which is slightly silty. Thin limestone beds are present throughout, especially below 1500 m RKB. Sand stringers and layers up to 4 m thick are present in the section above 1090 m RKB. The two cores penetrated sand units at 1442–1469 m RKB and 1330–1380 m RKB. Core 3 from the lower sandstone unit includes infrequent clay and silt interbeds, but the sand is generally coarse-grained and structureless. This unit is interpreted as a composite turbidite deposited on or near the basin floor. Core 2 from the upper arenaceous unit consists of fine-grained sand with frequent clay and silt laminations. Cross-bedding and planar laminations are present throughout the core, and the entire unit is interpreted to be of shallow marine origin.

3. Material and methods

The aborted pilot hole drilled down to 906 m was sampled with sidewall cores. From a depth of 567–885 m a total of 28 sidewall cores with a 10–20 m sample interval has been examined. Return of cuttings in the main hole started at 887 m. Cutting samples have been obtained with a 10 m sampling interval in most of the examined successions. In some intervals samples have been taken at 2–5 m intervals. Three conventional cores were taken at the following levels: 896–906.6 m, 1347.5–1374.4 m and 1460.5–1472 m. Among the sidewall cores from the main hole only six plugs from between 920 and 1022 m were available for this study. The biostratigraphic analyses from 887 to 1600 m are largely based on cutting samples, and consequently the biostratigraphic interpretation and correlation is based mainly on last-appearance datums (LADs) of the various taxa.

All the available sidewall cores, convential cores and cutting samples taken from 567 to 1600 m were analysed for foraminifera, dinoflagellates, radiolaria and diatoms. From some sample levels both sidewall cores and cuttings were analysed. For analyses of foraminifera in the conventional core samples and the cuttings, 50–110 g material was used. The foraminiferal identifications were done in the 0.07–0.50 mm fraction. Whenever possible, 300 individuals were counted in each analysis. In order to better identify the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity separated in heavy liquid. Less material was available from the sidewall cores (20–50 g from the pilot hole, and only 8–17 g from the main hole), and from these samples the material less than 0.1 mm was saved for palynological analyses. Palynomorphs were extracted from both cuttings and cores from 20–30 g material, using conventional preparation methods involving removal of carbonates and silica by HCl and HF, respectively. The organic residues were subsequently oxidized with nitric acid to remove pyrite and some of the amorphous organic matter.

The assemblage composition of radiolaria larger than 100 mm in diameter was recorded in the foraminifera preparations of the sidewall core material. A separate set of samples weighing approximately 20–30 g each from the cuttings and the convential cores was prepared for siliceous microfossil examination and split into the fractions <45 *μ*, 45–250 *μ* and >250 *μ*.

In addition to the biostratigraphic analyses, six samples from well 7316/5-1 and four samples from the Forlandsundet section were picked for strontium-isotope analysis (Table 1). The analyses were performed on the tests of *in situ* benthonic calcareous foraminifera. The tests representing the samples A_1 and A_2 in 7316/5-1 are from cutting samples from five different levels between 987 and 1015 m. Sample B is also from cuttings and represents four levels in the interval 1050–1070 m. In order to obtain sufficient material for the isotope analyses, it was necessary to combine material from different levels. Samples C_1–C_3 are all from 1472 m representing the lowermost conventional core. The samples 228M, 244M, 248M and 19M from Forlandsundet on Spitsbergen are from the section described by Feyling-Hanssen & Ulleberg (1984).

4. Biostratigraphic results

4.1 Well 7316/5-1

Foraminifera, dinoflagellates and radiolaria occur with variable abundance and diversity throughout the interval under investigation (587–1600 m). In addition to the fossil assemblages regarded as in place and representing the correct age of the sediments at the time of deposition, there are variable quantities of fossils derived from earlier depositional phases. These latter constituents are dominant in some parts of the section, which may be interpreted as lowstand fan complexes. Biostratigraphic subdivision of the Pleistocene–Upper Pliocene section is based entirely on foraminifera, as *in situ* dinoflagellates and radiolaria are very rare or absent. A total of seven informal foraminifera biozones (BB-FA to BB-FG), four informal dinoflagellate zones (BB-DA to BB-DD), and five radiolaria zones (BB-RA to BB-RE) are recognized in the Pleistocene to Middle Eocene strata of 7316/5-1. B = Barents Sea, B = Bjørnøya West (Figs. 5–7). Figures 5 and 6 contain range charts of the most important species. Eidvin et al. (1994) include range charts of all registered species, but without some modifications performed in this study.

4.1.1 Foraminifera zones

Foraminifera of variable diversity and assemblage composition occur in most of the investigated samples in the study interval (567–1600 m), but there are three intervals interpreted as being represented exclusively of redeposited older taxa, specimens redistributed as a result of drilling contamination (caved), or species with very long stratigraphic ranges. The assemblages from the bedrock section below the glaciogene overburden either have no equivalents in the Vøring scientific drillings or are more confidently correlated to sections in northern Europe. Consequently, it has been concluded that the most appropriate procedure under these circumstances is to employ a system of seven informal local zones, based primarily on the frequency of specimens regarded as *in situ*, and the ratio of calcareous and agglutinated tests.

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) – *ELPHIDIUM EXCAVATUM* – *CASSIDULINA RENIFORME* ZONE

Category: Informal local assemblage zone.

Designation: BB-FA.

Informal local boundary criteria: The top of the zone extends above the uppermost investigated sample (567 m) and probably near the sea floor. The base of the zone is marked by the lowest common occurrence of *N. pachyderma* (sin.), *E. excavatum* and *C. reniforme*.
Depth range: 567 (uppermost investigated sample) – 670 m.

Age: Pleistocene.

Material: Nine sidewall cores.

Equivalent zones: Assemblage Zone A of Eidvin et al. (1993) described from wells 7117/9-1 and 7117/9-2 on the Senja Ridge and 7119/7-1 in the Tromsø Basin. *Neogloboquadrina pachyderma* (sin., enc.) Zone of Spiegler & Jansen (1989) and Subzone NSB 16x of King (1989).

In-place assemblage: Calcareous benthonic foraminifera are numerous and diverse in the samples above 599 m, but both diversity and abundance decline below this depth. *E. excavatum* and *C. reniforme* are the most common species. Other important species are: *Islandiella islandica*, *Bulimina marginata*, *Nonion affine*, *Angulogerina fluens*, *Islandiella norcrossi*, *Cibicides lobatulus*, *Elphidium subarticum* and *Nonion labradoricum* (Fig. 5).

Planktonic foraminifera are less frequent than calcareous benthonic taxa, but they are also common above 599 m. *N. pachyderma* (both encrusted and unencrusted varieties of the sinistrally coiled individuals) is dominant. Other important species are: *N. pachyderma* (dextral) and *Turborotalia quinqueloba*.

Reworked assemblage: *Gyroidina soldaii girardana*, *E. variabilis* and probably *P. bulloides* are reworked Miocene and Oligocene taxa. The agglutinated species: *S. spectabilis*, *Ammodiscus* sp. and *Rabdammina* sp. indicate redeposition of Palaeogene or Mesozoic sediments. The planktonic species: *Heterohelix* sp. and *Hedbergella* sp. have been derived from Upper Cretaceous sediments.

Remarks: All of the benthonic calcareous foraminifera here regarded as *in situ* are extant species typically associated with Pliocene–Pleistocene deposits of the Norwegian margin. *N. pachyderma* (sinistral, encrusted) has its first frequent occurrence at 1.7 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). This test morphology has only sporadic occurrences in older sediments. *N. labradoricum* also appears to be restricted to Pleistocene deposits on the Norwegian shelf. King (1989) employs *N. labradoricum* as the nominate taxon for the Pleistocene Zone NSB 16x of the northern North Sea, and this zone has been recognized on the mid-Norwegian shelf by Eidvin & Riis (1991).

UNZONED INTERVAL f1

Depth range: 670–805 m.

Material: 13 sidewall cores.

Age: Late Pliocene–Pleistocene.

Assemblage: Foraminifera are generally rare in this interval, and 7 of the 13 samples are barren. The assemblage is of low diversity and consists exclusively of benthonic taxa. Sporadic, rare occurrences of: *Elphidium bartletti*, *Elphidium* sp., *Cibicidoides pachyderma* and *Gyroidina soldanii girardana* are the only calcareous representatives. The agglutinated tests, which are severely damaged and can only be identified to genus, include: *Ammodiscus* sp., *Bathysiphon* sp., *Glomospira* sp., *Textularia* sp., *Karreriella* sp., *Reticulophragmium* sp., *Haplophragmoides* spp. and *Reophax* sp. (Fig. 5).

The occurrence of *Gyroidina soldanii girardana* at 805 m is interpreted as the result of redeposition of Lower Oligocene–Lower Miocene sediments. The agglutinated taxa are reworked from older Cenozoic and Mesozoic deposits.

Remarks: Most of the calcareous foraminifera in this interval are characteristic of Pliocene–Pleistocene sediments, and only a general Late Pliocene to Pleistocene age can be inferred.

GLOBIGERINA BULLOIDES–CASSIDULINA TERETIS ZONE

Category: Informal local assemblage zone.

Designation: BB-FB.

Informal local boundary criteria: The top of the zone is taken at the down-hole reappearance of calcareous taxa, such as *Cassidulina teretis* and *Globigerina bulloides*. The base of the zone is marked by the lowest occurrences of *Cassidulina teretis* and *Globigerina bulloides*.

Depth range: 805–885 m.

Material: Five sidewall cores.

Age: Late Pliocene.

Equivalent zones: *Geodia* sp. – *Globigerina bulloides* Assemblage Zone (D) of Senja Ridge well 7117/9-1 (Eidvin et al. 1993). *Neogloboquadrina atlantica* (sin.) Zone of Spiegler & Jansen (1989). Questionably Subzone NSB 15a and Subzone NSP 15d of King (1989).

In-place assemblage: Although foraminifera are sparse in this interval, they are significantly more common than in the immediately overlying section. Benthonic calcareous species are rare and include: *N. affine*, *C. lobatulus*, *B. marginata*, *Cassidulina tertis*, *Haynesina orbiculare* and *Gyroidina soldanii girardana*. *Globigerina bulloides* and *N. pachyderma* (sin., unencrusted) are the only planktonic species. Additionally, rare specimens of the sponge, *Geodia* sp., occur in this zone (Fig. 5).

Reworked assemblage: Most of the foraminifera are agglutinated species, but few of the specimens can be identified to species level. The agglutinated species include: *Glomospira charoides*, *Bathysiphon* spp., *Ammodiscus* sp., *Reticulophragmium* sp., *Haplophragmoides* sp. and *Reophax* sp. These taxa are interpreted as having been derived from Palaeogene or Mesozoic sediments.

Remarks: The benthonic calcareous foraminifera are characteristic Pliocene–Pleistocene taxa, except for *Gyroidina soldanii girardana* (Early Oligocene–Early Miocene). *G. bulloides* is common in Upper Pliocene sediments older than 2.3 Ma on the Vøring Plateau (Spiegler & Jansen 1989).

UNZONED INTERVAL f2

Depth range: 885–949 m.

Material: Three conventional core samples taken from 897.4–905.2 m, two sidewall cores and five ditch cuttings samples at about 10 meters intervals.

Age: Late Pliocene.

Assemblage: Although the declines in the frequency and diversity at the upper boundary of this interval zone are not as severe as at the top of Unzoned Interval f1, most of the specimens in this interval are regarded as reworked. One specimen of *N. affine* and one indeterminate planktonic species are the only calcareous species.

The agglutinated fauna is poorly preserved and includes *Bathysiphon* sp. as the most common species. *G. charoides*, *R. placenta*, *Glomospira* sp., *Ammodiscus* sp. and *Haplophragmoides* sp. are also present. Most of these taxa are Mesozoic to Early Palaeogene in age. *R. placenta* has been reported from the Lower Eocene to Upper Miocene in the North Sea (King 1989).

Remarks: *N. affine* is most common in Pliocene–Pleistocene sediments, but occurs as early as the Oligocene. Unzoned Interval f2 occupies the base of what is interpreted as the glaciogene overburden, and is dated as Late Pliocene based on lithological correlation. There is a distinct lithologic break between the base of this zone and the underlying unit, which is also marked by a regional reflector.

RETICULOPHRAGMIUM PLACENTA ZONE

Category: Informal local partial range zone.

Designation: BB-FC.

Informal local boundary criteria: The top of the zone is taken at the highest consistent occurrence of *R. placenta*. The base of the zone is marked by the highest occurrences of *Turrilina alsatica* and *Angulogerina tenuistriata*.

Depth range: 948–982 m.

Material: Three sidewall cores and two ditch cutting samples.

Age: Early Oligocene–Early Miocene.

Equivalent zones: Questionably Zone NSA 10 of King (1989).

Assemblage: Only rare, agglutinated foraminifera occur in this zone. Although few in number, they are somewhat more common than in the overlying interval. *R. placenta* has a consistent but rare occurrence. Other important species are *Bathysiphon* spp., *Ammodiscus* sp., *Haplophragmoides* sp. and *Spiroplectammina* sp. (Fig. 5).

Remarks: In the North Sea *R. placenta* occurs in Lower Eocene to Middle Miocene sediments and additionally has a short occurrence in the uppermost Upper Miocene section (King 1989). The other agglutinated taxa are of Mesozoic or Palaeogene age, but some species may range as high as basal Miocene in the North Sea area (King 1989).

It is difficult to determine the precise age of this zone based on foraminifera. The sediments cannot be older than Early Oligocene, based on the age of the underlying zone. Only a general Early Miocene to Early Oligocene age can be inferred on the basis of the foraminifera. The dinoflagellate cysts distributions indicate an Early Miocene age for the sediments above 960 m, which are distinguished by a regional seismic reflector, but there are no discernible differences in the foraminifera fauna at this depth.

TURRILINA ALSATICA – ANGULOGERINA TENUISTRIATA ZONE

Category: Informal local total range zone.

Designation: BB-FD.

Informal local boundary criteria: The top of the zone is taken at the highest occurrence of *T. alsatica* and *A. tenuistriata*. The base of the zone is taken at the lowest consistent occurrence of *T. alsatica*.

Depth range: 982–1090 m.

Material: One sidewall core and 17 ditch cutting samples at 3–15 m intervals.

Age: Early Oligocene.

Equivalent zones: Questionably, Subzone NSB 7a or Subzone NSB 7b of King (1989) and Zone NSR 7A of Gradstein & Bäckström (1996).

Assemblage: Foraminifera are significantly more numerous in this interval than in the immediately overlying zone. Both calcareous benthonic and agglutinated taxa are present, but the calcareous species (mostly benthonic) are dominant. A single indeterminate planktonic foraminifera was observed at 1045 m. The two nominate species characterize the assemblages, although both species have sporadic rare occurrences in the ditch cuttings from the section below this zone. *T. alsatica* and *A. tenuistriata* are most common and occur through most of the unit. Other important species are: *Gyroidina s. girardana*, *Cibicides dutemplei*, *Eponides pygmeus*, *Stilostomella adolphina*, *Cibicides telegdi*, *Bolivina* cf. *antiqua*, *Globulina munsteri*, *Globulina inaequalis*, *Gyroidinoides* sp. 1 (Ulleberg 1974), *Cibicides aknerianus*, *Globocassidulina subglobosa* and *N. affine*. *R. placenta* and *Reticulophragmium* sp. are the dominant agglutinated taxa (Fig. 5).

Remarks: The calcareous taxa have been described previously from the Oligocene of the North Sea region, and some species also range into Lower Miocene sediments (Batjes 1958; Christensen & Ulleberg 1974, 1985; Nuglish & Spiegler 1991; Spiegler 1974; King 1989). *Bolivina* cf. *antiqua* is restricted to Upper Oligocene–lowermost Miocene sediments in the North Sea (King 1989), but this species has been recorded from Lower Oligocene deposits on the Nordland Ridge (Mid-Norway) (Eidvin et al. in press).

Strontium-isotope analyses of these tests give an age of about 35 m.y., i.e. Early Oligocene (Table 1 and Fig. 7).

A similar fauna from an outcrop at Forlandsundet, Spitsbergen was described by Feyling-Hanssen & Ulleberg (1984), who interpreted the section as transitional Early/Late Oligocene in age. King (1989) correlated the fauna from this locality with Subzones NSB 8a or NSB 7b (Early/Late Oligocene) of his North Sea zonation.

Strontium-isotope analyses of tests from the Forlandsundet section give an age of 27.5–29.5 m.y., i.e. early Late Oligocene (Table 1).

Two regional seismic reflectors have been identified within this zone (Fig. 5). The strong seismic reflector at about 1040 m coincides approximately with minor changes in the foraminiferal assemblage, but neither the fauna nor the strontium-isotope analyses indicate a major hiatus. A weak seismic reflector is noted at 1009 m, but there is no change in the foraminifera fauna across this reflector. The base of the BB-FD Zone also coincides with a regional seismic reflector.

UNZONED INTERVAL f3

Depth range: 1090–1270 m.

Material: 18 ditch cutting samples at 2–18 m intervals.

Age: Middle Eocene (based on other biostratigraphical evidence).

Assemblage: Very few foraminifera occur in this interval. Single specimens of the calcareous benthonic species: *A. tenuistriata*, *E. pygmeus*, *G. subglobosa* and *Cassidulina* sp. were recovered from the upper part of the interval. *Cibicides* spp. and *Nonionella spissa* were recovered from the lower part of the interval. Most of the calcareous specimens from the upper part of the interval are probably caved from the overlying section.

Agglutinated taxa are somewhat more numerous but generally poorly preserved. *Bathysiphon* sp. is the most common species, but *R. placenta*, *Spiroplectammina carinata*, *Glomospira* sp., *Reticulophragmium* sp., *Haplophragmoides* sp. and *Recurvoides* sp. are also present (Fig. 5).

Remarks: Many of the calcareous specimens in the lower part of the interval and most of the agglutinated forms are poorly preserved. This indicates that most of these are reworked. Most of these forams are long ranging stratigraphically. An exception to this is *N. spissa* which is known from the Middle Eocene of Belgium (Kaasschieter 1961) and *S. carinata* which is known from Lower Eocene to Lower Oligocene in the North Sea (Charnock & Jones 1990). Both of these forms are found as single specimens near the base of the interval.

CIBICIDES PROPRIUS – SPIROPLECTAMMINA NAVARROANA – PSEUDOHASTIGERINA MICRA – PSEUDOHASTIGERINA SP. ZONE

Category: Informal local partial range zone.

Designation: BB-FE.

Informal local boundary criteria: The top of the zone is taken at the highest occurrence of *S. navarroana* and *Pseudohastigerina* sp. The base of the zone is marked by the highest occurrence of *Vaginulinopsis decorata*.

Depth range: 1270–1465 m.

Material: Two conventional core samples from a depth of 1356.5–1363.6 m and 18 ditch cutting samples at 2–17 m intervals.

Age: Early Middle Eocene.

Equivalent zones: Zone NSP 7 of King (1989) and, questionably, Zone NSR 5A of Gradstein & Bäckström (1996).

Assemblage: Agglutinated foraminifera dominate the moderately rich fauna, but some calcareous taxa are also present. *R. placenta* is the most common agglutinated species, *S. navarroana*, *S. carinata*, *Bathysiphon* spp., *Reticulophragmium* spp., *Haplophragmoides* spp. and *Cribrostomoides* sp. are also present (Fig. 5).

Among the calcareous assemblages, benthonic species are most common, and *C. proprius* has the most consistent distribution. *Bulimina ovata*, *Cibicides* sp., *Pullenia* sp., *Alabamina* sp. and *Quinqueloculina impressa* have more sporadic occurrences. There are irregular occurrences of the planktonic species *Pseudohastigerina micra* and *Pseudohastigerina* sp.

Remarks: The calcareous foraminifera found in this zone are all previously described from Palaeogene deposits in western and central Europe. *C. proprius* is described from the Lower–Upper Eocene of The Netherlands (Doppert & Neele 1983) and Belgium (Kaasschieter 1961). *B. ovata* is described from the Lower Eocene of the DSDP Site 338 on the Vøring Plateau (Hulsbos et al. 1989) and from Upper Eocene deposits in Belgium (Kaasschieter 1961). *Q. impressa* is known from the Middle Eocene in The Netherlands and from Upper Eocene sediments in Belgium and England (Kaasschieter 1961).

The planktonic species *P. micra* was described from the Lower to Upper Eocene section of The Netherlands (Doppert & Neele 1983). King (1989) has described a *Pseudohastigerina* spp. (Zone NSP 7) from the lower Middle Eocene of the North Sea.

The agglutinated species *R. placenta* is described from the Lower Eocene to Upper Miocene of the North Sea (King 1989). *S. navarroana* is described from the Lower–Middle Eocene of the North Sea and Haltenbanken (Gradstein et al. 1994; Gradstein & Bäckström 1996). *S. carinata* is known from the Lower Eocene to Lower Oligocene in the North Sea (Charnock & Jones 1990). The other agglutinated taxa are characterized by long stratigraphic ranges including the Mesozoic and Palaeogene.

CIBICIDES PROPRIUS – VAGINULINOPSIS DECORATA – SPIROPLECTAMMINA NAVARROANA – PSEUDOHASTIGERINA MICRA ZONE

Category: Informal local total range zone.

Designation: BB-FF.

Informal local boundary criteria: The top and bottom of the zone are taken at the highest occurrence and lowest consistent occurrence of *V. decorata*.

Depth range: 1465–1572 m.

Material: Two conventional core samples from a depth of 1465–1472 m and 11 ditch cutting samples at approximately 10 m intervals.

Age: Early Middle Eocene.

Equivalent zones: Zone NSP 7 of King (1989) and questionably Zone NSR 5A of Gradstein & Bäckström (1996).

Assemblage: A rather rich foraminifera fauna of both calcareous and agglutinated species occur in the zone. The benthonic calcareous taxa include: *C. proprius*, *V. decorata*, *B. ovata* and *Anomalina ypresiensis* as the most common species. *Anomalina acuta*, *Alabamina midwayensis*, *Elphidium latidorsatum*, *Lenticulina cultrata*, *Planulina burlingtonensis* and *Pullenia quinqueloba* are also present (Fig. 5).

The only planktonic species, *Pseudohastigerina micra*, has a rare and sporadic distribution in Zone BB-FF.

The agglutinated fauna includes *R. placenta* and *S. navarroana*, which are the most common species and occur through the whole zone. *S. carinata*, *Bathysiphon* sp., *Reticulophragmium* sp. and *Cribrostomoides* sp. are also present.

Remarks: The previous known distribution of *C. proprius* and *B. ovata* in western and central Europe is described above under Zone BB-FE. *V. decorata* has been reported from Middle–Upper Eocene strata in The Netherlands (Doppert & Neele 1983) and Upper Eocene of Belgium (Kaasschieter 1961). *V. decorata* has a rare and sporadic distribution in Lower Eocene sediments on the Vøring Plateau (DSDP 338) (Hulsbos et al. 1989). *A. ypresiensis* and *A. acuta* are described from the Lower-Middle Eocene in Belgium (Kaasschieter 1961; Doppert & Neele 1983). *A. midwayensis* is described from the Upper Palaeocene–Lower Eocene in The Netherlands (Doppert & Neele 1983), while *E. latidorsatum* is reported from the Lower Eocene in Belgium (Kaasschieter 1961). *L. cultrata* is described from the Lower Eocene to Lower Oligocene (most common in the Middle Eocene) in The Netherlands (Doppert & Neele 1983). *P. burlingtonensis* is known from the upper Lower–Middle Eocene in The Netherlands (Doppert & Neele 1983), and from the Eocene in Belgium (Kaasschieter 1961). *P. quinqueloba* is described from Lower Eocene sediments on the Vøring Plateau (Hulsbos et al. 1989) and from the Upper Eocene in Belgium (Kaasschieter 1961).

The known stratigraphic ranges of *R. placenta*, *S. navarroana*, *S. carinata* and *P. micra* were discussed above under Zone BB-FE.

The recovered foraminifera fauna suggests an early Middle Eocene age for Zone BB-FF in 7316/5-1. A strontium-isotope analysis on the tests recovered in the core sample at 1472 m in the uppermost part of the zone give an age of 46–47 m.y., i.e. early Middle Eocene (Table 1 and Fig. 7).

SPIROPLECTAMMINA NAVARROANA – SPIROPLECTAMMINA CARINATA ZONE

Category: Informal local partial range zone.

Designation: BB-FG.

Informal local boundary criteria: The top of the zone is taken at the lowest consistent occurrence of *V. decorata*. The base of the zone is undefined.

Depth range: 1572–1600 m (lowest sample analysed).

Material: Four ditch cutting samples at 10 m intervals.

Age: Early Middle Eocene.

Equivalent zones: Questionably, Zone NSR 5A of Gradstein & Bäckström (1996).

Assemblage: The assemblage consists almost exclusively of agglutinated foraminifera. *R. placenta* dominates the fauna, but *S. carinata*, *S. navarroana*, *Bathysiphon* sp. and *Reticulophragmium* sp. are also important constituents. Only one specimen of the calcareous form *V. decorata* has been found in the uppermost sample (Fig. 5).

Remarks: The known stratigraphic ranges of *R. placenta*, *S. carinata* and *S. navarroana* were discussed above under Zone BB-FE. An early Middle Eocene age is inferred for the zone.

4.1.2 Dinoflagellate zones

The dinoflagellate biostratigraphy as of well 7316/5-1 is partly correlated to the zonation defined in the ODP Leg 104, Site 643 on the Vøring Plateau (Manum et al. 1989; Mudie 1989). However, many of the stratigraphically important species described from ODP Leg 104, Site 643 have not been recovered in 7316/5-1, and the present correlations are thus regarded as tentative. The stratigraphic interval between 567 and 948 m contains only sporadic *in situ* dinoflagellates, and it has not been possible to make correlations to any of the Vøring Plateau dinoflagellate zones in this interval. Below 992 m four informal dinoflagellate zones are identified which are partly correlated to the zones defined by Manum et al. (1989) on the Vøring Plateau.

UNZONED INTERVAL d1

Depth range: 578–948 m.

Material: Five ditch cutting samples at 8–10 m intervals, 19 sidewall cores at 4–46 m intervals, 1 core at 905.2 m.

Assemblage: The interval between 567 and 948 m is rich in dinoflagellates (more than 140 species are identified), but only very few of these are interpreted to be *in situ*. Typical Pliocene–Pleistocene forms such as *Achomosphaera andalousiensis* (656 m) and *Bitectatodinium tepikiense* (676 m) are observed, but these species may also occur in the Miocene and Holocene. The rich and

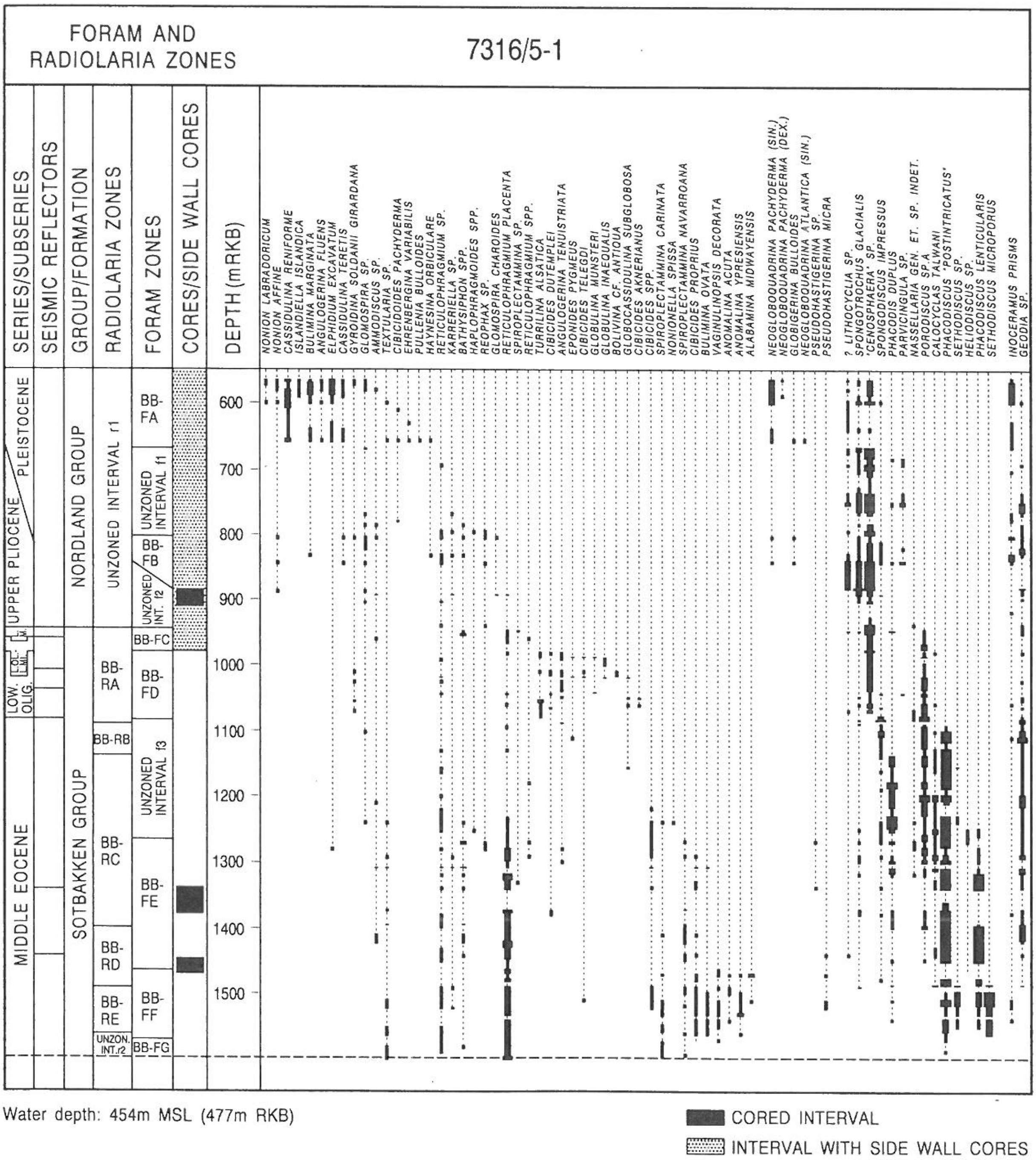

Fig. 5. Range chart of the most important foraminifera and radiolaria in the investigated interval of well 7316/5-1.

diversified dinoflagellate flora contains dominantly recycled Palaeogene (i.e. Upper Palaeocene–lowermost Eocene, Middle Eocene and Lower Oligocene) species, but there are also reworked Jurassic, Lower and Upper Cretaceous, and Miocene dinoflagellates in this Pleistocene–Upper Pliocene unit.

Remarks: Both *A. andalousiensis* and *B. tepikiense* are extant species (Harland 1992), and their stratigraphic ranges extend back to the Middle Miocene (mid-Serravalian Stage) and basal Miocene, respectively (Williams et al. 1993). These two very limited occurrences provide only marginal evidence of a broadly Neogene age for the upper part of the interval, which is inadequate for meaningful correlation. Therefore, the interval has not been zoned.

UNZONED INTERVAL d2

Depth range: 948–960 m.

Material: Two sidewall cores at 948 m and 955 m, one ditch cutting sample at 950 m.

Age: Early Miocene.

Assemblage: The interval contains a moderately rich and fairly diverse dinoflagellate flora, but only few of these are *in situ*. *Lejeunecysta hyalina* and *Apteodinium* sp. 1 occur in all three samples from the zone. *Pentadinium laticinctum* is found at 955 m. *Impagidinium patulum* occurs in the samples from 948 m and 950 m (Fig. 6). According to Manum et al. (1989) *I. patulum* does not occur in sediments older than Early Miocene in Leg 104, Site 643 on the Vøring Plateau. According to Powell (1992) the oldest occurrence of *I. patulum* coincides with the base of nannofossil biozone NN2. *Spiniferites pseudofurcatus* is noted in the samples from 950 m and 955 m. This species is common in the Lower Miocene, but is also found in older deposits.

Cordosphaeridium cantharellum is recorded at 948 m and 955 m. This species does not usually occur in sediments younger than Early Miocene (Powell 1992), and it does not occur above the Lower Miocene beds in Leg 104, Site 643 on the Vøring Plateau (Manum et al. 1989). The samples at 950 m and 955 m also contain *Invertocysta tabulata*. On the Vøring Plateau this species is restricted to the Lower Miocene (Manum et al. 1989). *Systematophora placacantha* has its youngest occurrence at 950 m. According to Powell (1992), this species does not usually range above the Middle Miocene. *Hystrichosphaeropsis obscura* noted at 955 m usually has a restricted occurrence in the Miocene (Powell 1992). The presence of *Problematicum* sp. IV Manum 1976 at 955 m is also noteworthy. Manum et al. (1989) found this species only in the Lower Miocene in Leg 104, Site 643 on the Vøring Plateau.

Recycled dinoflagellates in this zone include Upper Jurassic, Lower Cretaceous, Upper Cretaceous and Palaeogene taxa.

Remarks: The lowest occurrence of *I. patulum* is here found in the underlying zone due to caving. Both the upper and the lower boundary of the interval coincide with seismic reflectors. Across the upper boundary there is a marked lithological change.

UNZONED INTERVAL d3

Depth interval: 960–992 m.

Material: Four ditch cutting samples at 2–10 m intervals, one sidewall core at 970 m.

Assemblage: More than 50 species of dinoflagellates are recorded from this unit. Most of these are, however, reworked and no *in situ* forms which can be used for age determination of this interval were recorded. Species of unspecified Eocene–Early Oligocene age dominate the assemblages, but recycled Upper Palaeocene–lowermost Eocene, Upper Cretaceous and Lower Cretaceous species are also present.

Remarks: A general Early Oligocene to Early Miocene age is inferred for this zone based on its stratigraphic position in relation to the overlying Early Miocene interval and the underlying Early Oligocene BB-DA Zone.

ZONE BB-DA

Category: Informal local concurrent range zone.

Designation: BB-DA.

Informal local boundary criteria: Interval from lowest appearance of *Impagidinium* sp. 1 to the uppermost occurrence of *Chiropteridium mespilanum* at 992 m.

Depth range: 992–1010 m.

Material: Two ditch cutting samples at 992 m and 1000 m.

Age: Early Oligocene.

Equivalent zone: Partly time-equivalent to the *Impagidinium* sp. 1 Zone of Manum et al. (1989).

Assemblage: More than 30 species of dinoflagellates were recorded in this zone. Most of these are reworked from Eocene–Lower Oligocene deposits, but also recycled Cretaceous taxa have been found. *Chiropteridium mespilanum* occurs at 992 m (Fig. 6). This species is regarded as a stratigraphic marker typical for uppermost Lower Oligocene to lowermost Upper Oligocene strata (Powell 1992). In Leg 104, Site 643 on the Vøring Plateau this species is restricted to the Upper Oligocene *Systematophora* sp. 1 Zone of Manum et al. (1989). Strontium-isotope analyses from Zone BB-DA in 7316/5-1 give, however, an Early Oligocene age of ca. 35 Ma. This inconsistency may be explained by the diachronous appearance of the biostratigraphic marker fossils or that the age of the *Impagidinium* sp. 1 Zone on the Vøring Plateau is poorly constrained (in contrast to many of the other biozones in Leg 104, Site 643, there is no palaeomagnetic control on the age in this zone). It is also possible that the key fossil *Impagidinium* sp. 1 is caved at 1000 m in 7316/5-1. Since we have no firm evidence of Upper Oligocene deposits in the well, this latter explanation is not very likely.

Remarks: The lower boundary of Zone BB-DA coincides with a seismic reflector, which is rather poorly expressed at the drill site but becomes stronger towards the east.

ZONE BB-DB

Category: Informal local interval zone.

Designation: BB-DB.

Informal local boundary criteria: Interval from the lowest appearance of *Impagidinium* sp. 1 down to the appearance of *Glaphyrocysta paupercula* at 1080 m.

Depth range: 1010–1080 (1090) m.

Material: 13 ditch cutting samples at 3–15 m intervals, 1 sidewall core at 1022 m.

Age: Early Oligocene.

Equivalent zone: Partly time-equivalent to the *Areosphaeridium*? *actinocoronatum* Zone of Manum et al. (1989).

Assemblage: Zone BB-DB contains a moderately rich and fairly diverse dinoflagellate microflora. Several of the recorded species have a relatively broad stratigraphic range in the Palaeogene, and the frequency relation between *in situ* Oligocene forms and reworked Eocene specimens is difficult to determine. *Lejeunecysta hyalina* has a consistent appearance through the zone. Other common species are *Apteodinium* sp. 1, *Deflandrea phosphoritica*, *Wetzeliella articulata*, *Systematophora ancyrea*, *Cribroperidinium giuseppei*, *Phthanoperidinium amoenum*, *Spiniferites pseudofurcatus*, *Cordosphaeridium cantharellum* and *Palaeoperidinium* sp. 1 (Fig. 6). Among these *Cribroperidinium giuseppei*, *Phthanoperidinium amoenum* and *Wetzeliella articulata* are not usually found in sediments younger than Early Oligocene. The occurrence of *Deflandrea* sp. B at 1020 m could also be of some stratigraphic significance, as this species is not found above the *Areosphaeridium*? *actinocoronatum* Zone in Leg 104, Site 643 on the Vøring Plateau (Manum et al. 1989). The presence of *Glaphyrocysta paupercula* at 1080 m is indicative of an an Early Oligocene age at this level. According to Powell (1992) this species is restricted to the earliest Oligocene RPe Zone.

Reworked dinoflagellates of definite Eocene age are fairly common in the zone, and include species restricted to the Middle Eocene. In addition, typical Upper Palaeocene-lowermost Eocene, Upper Cretaceous and Lower Cretaceous species are found at several levels.

Remarks: On the Vøring Plateau the *Areosphaeridium*? *actinocoronatum* Zone of Manum et al. (1989) is interpreted to cover the upper Lower Oligocene and lower Upper Oligocene strata. In 7316/5-1 *Reticulatosphaera actionocoronata* has a single occurrence at 1080 m. An Early Oligocene age of 35 Ma for Zone BB-DB is determined from strontium-isotope analyses. The lower boundary of the Lower Oligocene sequence probably extends down to the seismic reflector at 1090 m.

ZONE BB-DC

Category: Informal local interval zone.

Designation: BB-DC.

Informal local boundary criteria: The lower boundary is recognized by the lowest appearance of *Areosphaeridium arcuatum*. The upper boundary coincides with the appearance of *G. paupercula*.

Depth range: 1080 (1090)–1240 m.

Material: 12 ditch cutting samples at 3–20 m intervals.

Age: Middle Eocene.

Equivalent zone: Partly the *Areosphaeridium arcuatum* Zone of Manum et al. 1989.

Assemblage: The zone contains a moderately rich and diverse dinoflagellate flora (more than 50 species are recorded). *Deflandrea phosphoritica*, *Lejeunecysta hyalina*, *Wetzeliella articulata*, *Phthanoperidinium amoenum*, *Apectodinium homomorphum*, *Homotryblium tenuispinosum* and *Dapsilidinium simplex* are most common. Other characteristic species are *Systematophora ancyrea*, *Hystrichosphaeridium tubiferum*, *Kisselovia clathrata*, *Nummus* sp. A, *Cerebrocysta bartonensis*, *Adnatosphaeridium vittatum*, *Spiniferites pesudofurcatus*, *Cordosphaeridium cantharellum*, *Spiniferites sp.* 2 Manum et al. 1989, *Heteraulacacysta leptalea*, *Lentinia serrata* and *Samlandia chlamydophora* (Fig. 6). The oldest occurrence of *Corrudinium incompositum* at 1120 m might be of some stratigraphic significance. This species usually has its oldest occurrence in the Middle Eocene, i.e. in sediments correlatable to nannoplankton Zone NP 16 (Powell 1992).

Remarks: As discussed for Zone BB-DB the boundary between Zones BB-BD and BB-DC probably should be placed at the seismic reflector at 1090 m. Considerably fewer reworked specimens are found in this zone compared with the younger zones above. The presence of *Apectodinium quinquelatum* is evidence that Upper Palaeocene–lowermost Eocene strata have been redeposited into this Middle Eocene sequence. As in the overlying zones, recycled Cretaceous dinoflagellates are found at several levels in Zone BB-DC.

ZONE BB-DD

Category: Informal local interval zone.

Designation: BB-DD.

Informal local boundary criteria: Interval from the lowest appearance of *Adnatosphaeridium vittatum* to the lowest appearance of *Areosphaeridium arcuatum*.

Depth range: 1240–1600 m (lowermost studied sample).

Material: 32 ditch cutting samples at 3–20 m intervals, 4 sidewall cores at 1356.5 m, 1363.6 m, 1367.5 m and 1472.1 m.

Age: Middle Eocene.

Equivalent zone: Partly the *Adnatosphaeridium vittatum* Zone of Manum et al. (1989).

Assemblage: A rather rich and diverse (more than 70 species recorded) dinoflagellate flora has been recovered from this zone. Species which are common and have a fairly consistent appearance through the zone are: *Deflandrea phosphoritica*, *Lejeunecysta hyalina*, *Wetzeliella articulata*, *Cribroperidinium giuseppei*, *Phthanoperidinium amoenum*, *Thalassiphora delicata*, *Apectodinium homomorphum*, *Nummus* sp. A, *Adnatosphaeridium vittatum*, *Heteraulacacysta leptalea* and *Lentinia serrata*. Other characteristic species are: *Phthanoperidinium comatum*, *P. geminatum*, *P. levinumum*, *Areosphaeridium dictyoplokus*, *Deflandrea denticulata*, *Thalassiphora pelagica*, *Glaphyrocysta ordinata*, *Kisselovia clathrata*, *Dapsilidinium simplex*, *Pentadinium laticinctum*, *Lejeunecysta fallax*, *Selenopemphix nephroides*, *Spiniferites pseudofurcatus*, *S. cornutus*, *Caligodinium amiculum* and *Araneosphaera araenosa* (Fig. 6).

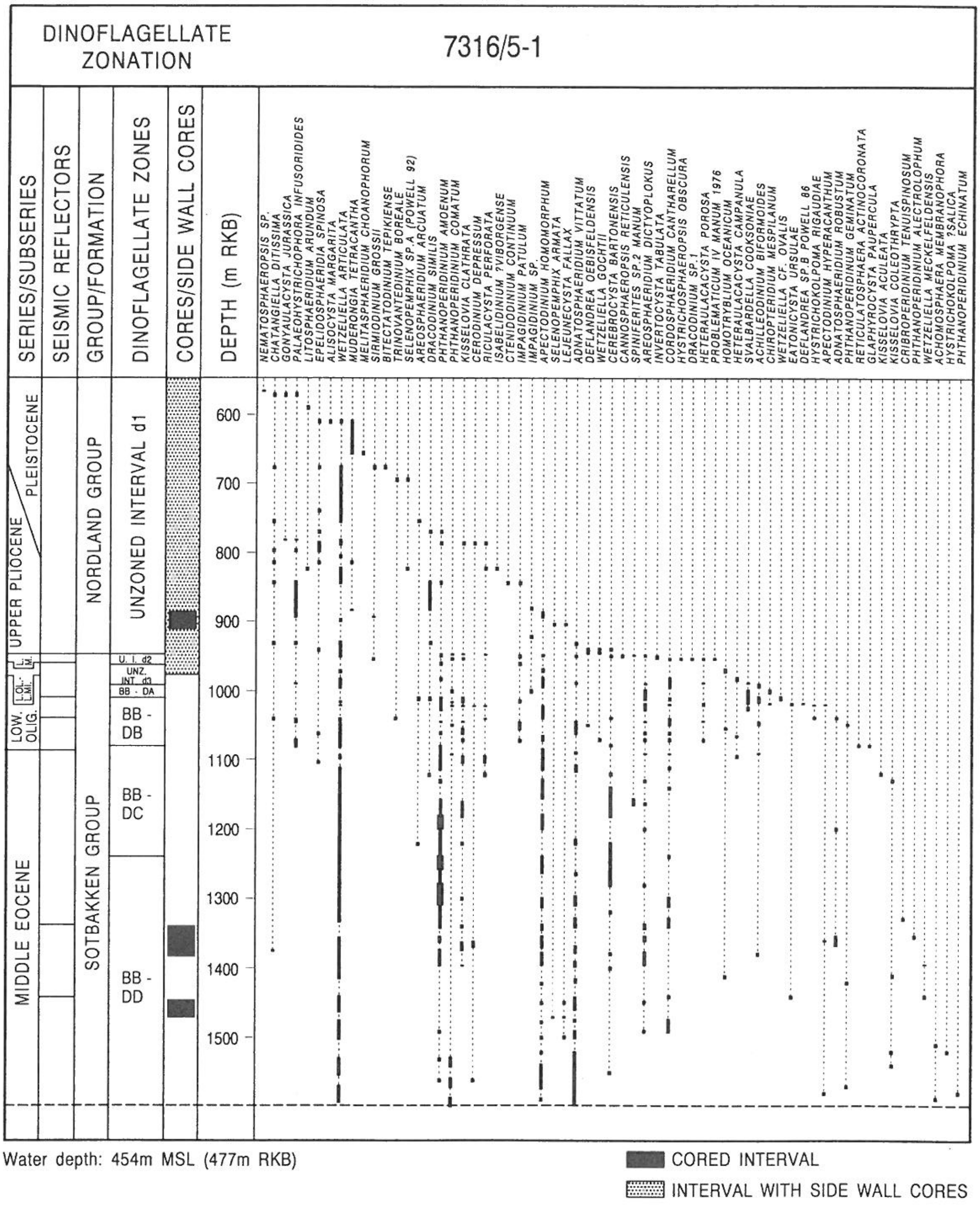

Fig. 6. Range chart of the most important dinoflagellates in the investigated interval of well 7316/5-1.

Remarks: The occurrences of *Phthanoperidinium comatum* (1600 m) and *P. geminatum* (1572) in the lowermost studied part of the zone suggest an age not older than Middle Eocene. The oldest occurrence of *Homotryblium oceanicum* at 1412 m is also evidence of an age not older than Middle Eocene at this level. Wetzeliella meckelfeldensis which is recorded at 1397 m, does not usually occur above the Middle Eocene (Powell 1992). The youngest *in situ* appearances of *Thalassiphora delicata* at 1300 m and *Eatonicysta ursulae* 1440 m also indicate an age not younger than Middle Eocene. The oldest occurrence of *Cerebrocysta bartonensis* is noted at 1400 m. Normally, this species first appears in the Middle Eocene. In Leg 104, Site 643 on the Vøring Plateau *C. bartonensis* is restricted to the *Adnatosphaeridium vittatum* Zone (Manum et al. 1989).

The proportion of reworked dinoflagellates is low in Zone BB-DD compared with in the overlying post-Eocene zones in the well. There is, however, evidence of reworking from the Upper Palaeocene–lowermost Eocene, Upper Cretaceous and Lower Cretaceous into these Middle Eocene deposits in 7316/5-1.

4.1.3 Radiolaria zones

Five new radiolaria zones are defined for the section in 7316/5-1, based on the distribution of 14 species. All of the observed specimens are in the opal-CT recrystallized phase or are pyrite replacements. Consequently, the preservation state is inadequate for detailed taxonomy, although internal structures are partially visible on some specimens. There are distinctive changes in this limited assemblage that permit biostratigraphic zonation, and it is clear that further studies will improve the chronostratigraphic resolution of these Radiolaria.

Five of the taxa in this assemblage have not been previously observed elsewhere, and their stratigraphic ranges are unknown: ?*Lithocyclia* sp., *Porodiscus* sp. A, *Nasellaria* gen. et sp. indet., *Sethmodiscus microporus* Haeckel 1887, and *Sethmodiscus* sp. Of these, *Porodiscus* sp. A and *Sethmodiscus microporus* are the nominate taxa and boundary criteria for two new zones. The remaining fauna has been observed in sediments from the Vøring Plateau or the North Sea. Seven of these taxa: ?*Lithocyclia* sp., *Spongodiscus impressus* Lipman 1952, *Phacodiscus duplus* Kozlova 1966, *Phacodiscus 'postintricatus'*, *Phacodiscus lenticularis* (Grzybowski 1896), *Sethmodiscus microporus* and *Sethmodiscus* sp. are commonly identified as ?spherical Radiolaria or *Cenosphaera* sp. by other micropalaeontologists. However, the assemblage so designated represents a taxonomically diverse collection of species, none of which met the generic definition of *Cenosphaera*. This name is totally unsuitable for these multichambered species, and a taxonomic revision is clearly necessary. The designation, '*Cenosphaera*' sp., is used here only for pyritized internal moulds lacking any indication of pore morphology, which are common to abundant in the glaciomarine sediments at this locality.

UNZONED INTERVAL r1

Depth: 567–948 m.

Assemblage: The most conspicuous member of this assemblage is '*Cenosphaera*' sp., which is abundant in 11 samples from this interval and is the dominant microfossil in the samples at 695, 739 and 754 m. ?*Lithocyclia* sp. and *Spongotrochus glacialis* have more consistent distributions in this interval than in the underlying section, where occurrences may result from caving. Specimens of both species are poorly preserved. There are six rare or common occurrences of the Cretaceous genus, *Parvicingula*, in this interval, and the pyritized specimen at 1045 m is regarded as caved.

Remarks: This interval has been dated as Late Pliocene–Pleistocene in age on the basis of foraminifera, but no indisputable Neogene Radiolaria have been observed. Opal-CT replaced Radiolaria of Cretaceous to Eocene age are variably abundant in this section and indicate extensive sediment redeposition from sources previously buried at depths exceeding 1500 m.

Spongotrochus glacialis is extant, and well-preserved specimens are common in Cenozoic siliceous sediments of the Norwegian Sea. The affinities and age of ?*Lithocyclia* sp. are unknown. Abundant occurrences of '*Cenosphaera*' sp. have been observed (RMG) in sediments of the Central Graben correlative with NSP 5 Zone of King (1989). The presence of abundant specimens of this problematical species is an indication of extensive redeposition of Lower Eocene sediments.

PORODISCUS SP. A ZONE

Category: Partial range zone.

Designation: BB-RA.

Definition: The top of the zone is taken at the highest occurrence of *Porodiscus* sp. A. The base of the zone is taken at the highest occurrence of *Phacodiscus 'postintricatus'*.

Status: new.

Depth range: 948–1095 m.

Material: Five sidewall cores from a depth of 948–1022 m and 21 ditch cutting samples at 2–10 m intervals.

Age: Early Miocene to Early Oligocene (based on other biostratigraphical evidence).

Equivalent zones: *Lithomitra* sp. A Zone of Bjørklund (1976) to *Eucyrtidium saccoi* Zone of Goll & Bjørklund (1989). Units VI to IX of Dzinoridze et al. (1978).

Assemblage: Radiolaria are consistently rare to common throughout this interval, with abundant and dominant occurrences restricted to the top and bottom of the zone. '*Cenosphaera*' sp. and *Porodiscus* sp. A are the only taxa with consistent occurrences. '*Cenosphaera*' sp. is rare to abundant in the interval 948 m (swc)–1070 m (dc). *Spongotrochus glacialis* has an irregular distribution in the interval 950 m (dc)–1092 m (dc). The top of the consistent range of *Spongodiscus impressus* occurs at 1080 m (dc) (Fig. 5).

Probable reworked occurrences include: the two single-specimen occurrences of *Calocyclas talwani* at 982 and 1060 m; the rare occurrence of *Parvicingula* sp. at 1045 m; and the rare occurrence of *Phacodiscus duplus* at 1045 m (dc). The rare occurrence ?*Lithocyclia* sp. is not regarded as *in situ*.

Remarks: Hughes (1981) reports consistent occurrences of '? spherical Radiolaria' in a borehole section from the southern North Sea (Flemish Bight) dated as Early Rupelian (his zones A–D). Although the photograph is of inadequate quality for conclusive identification, the faceted and somewhat angular shape of the '? spherical Radiolaria' (Hughes 1981, pl. 15.3, fig. 16) has similarities to *Porodiscus* sp. A and can be regarded as a weak indication of an Early Oligocene age for the *Porodiscus* sp. A Zone. However, *Porodiscus* sp. A has not been observed in the Lower Oligocene *Lithomitra* sp. A Zone of DSDP Site 337 (Bjørklund 1976; RMG, pers. obs.).

Both the top and bottom of this zone are approximately coincident with regional seismic reflectors, and both contacts are probably disconformable.

The consistent distribution of *'Cenosphaera'* sp. in frequencies ranging from rare to abundant in both ditch cutting and sidewall cores suggests that these occurrences are not the result of caving. Redeposition of significant quantities of Lower Eocene sediment must have occurred during the *Porodiscus* sp. A Chron.

PHACODISCUS 'POSTINTRICATUS' ZONE

Category: Partial range zone.

Designation: BB-RB.

Definition: The top of the zone is taken at the highest consistent occurrence of *Phacodiscus 'postintricatus'*. The base of the zone is taken at the highest occurrence of *Phacodiscus duplus*.

Status: new.

Depth range: 1095–1130 m.

Material: Five ditch cutting samples at 7–10 m intervals.

Age: Middle Eocene.

Equivalent zones: *Artostrobus quadriporus* Zone of Bjørklund (1976). Unit V of Dzinoridze et al. (1978).

Assemblage: Radiolaria are generally more numerous in this interval than in the *Porodiscus* sp. A Zone, but they are not present in the dominant frequencies that characterize some horizons in the two immediately underlying zones. The most conspicuous representatives of this zone are: *Phacodiscus 'postintricatus'*, *Spongodiscus impressus* Lipman and *Porodiscus* sp. A. Occurrences of *Calocyclas talwani* at 1103 and 1130 m are regarded as reworked (Fig. 5).

Remarks: *P. 'postintricatus'* does not occur in the *Calocyclas talwanii* and *Lophocorys norwegiensis* zones (Bjørklund 1976) of DSDP Site 338 (RMG; pers. obs.). Zone BB-RB is interpreted as stratigraphically younger than the *L. norwegiensis* Chron and is probably correlative with Zone NP 17 of Martini (1971). The *P. 'postintricatus'* Zone assemblage has not be observed in a continuously cored interval and consequently is poorly understood.

Phacodiscus 'postintricatus' differs from *'Cenosphaera'* sp. in its larger size, more discoidal shape and the surface preservation of pore morphology, which has been described as 'reticulate' by some authors.

PHACODISCUS DUPLUS ZONE

Category: Total consistent range zone.

Designation: BB-RC.

Definition: The top and base of the zone are defined at the highest consistent occurrence and lowest consistent occurrences of *Phacodiscus duplus*.

Status: new.

Depth range: 1130–1400 m.

Material: Two samples from core 2 at 1356.5 and 1363.6 m and 22 ditch cutting samples at 2–18 m intervals.

Age: Middle Eocene.

Equivalent zones: No clear equivalents on the Vøring Plateau.

Assemblage: Radiolaria are more numerous in this interval than in the two overlying zones, as a result of abundant occurrences of *Phacodiscus duplus*, *Phacodiscus 'postintricatus'* and *Porodiscus* sp. A. Radiolaria diversity is highest in this zone (9 species), which is partly the result of very extensive caving artefacts. All of the rare-to-abundant occurrences of *P. 'postintricatus'* and *Porodiscus* sp. A are interpreted as the result of caving. Additionally, the sporadic occurrences of *Spongodiscus impressus*, indeterminate Nassellaria, and very poorly preserved *Spongotrochus glacialis* may also be caved. *P. duplus* is absent at 1260 and 1280 m. *Calocyclas talwani* is rare to common and relatively consistent in its occurrence, particularly below 1200 m (dc). The rare occurrences of *Heliodiscus* sp. in the ditch cuttings at 1252, 1260, and 1270 m may be *in situ*. *Phacodiscus lenticularis* persists in reduced frequencies in the lower part of zone up to 1232 m (Fig. 5).

Remarks: The application of a stratigraphic first occurrence as a zonal boundary criterion is risky in a section controlled largely by ditch cutting samples, particularly in sections characterized by extensive caving artefacts. The distribution of *P. duplus* is disrupted by the sand unit at 1340–1365 m, where *in situ* radiolaria are very rare and *P. duplus* is absent. Otherwise, *P. duplus* has an essentially consistent occurrence in this section, and its base is clearly defined.

The occurrence of *P. duplus* at DSDP Site 338 is restricted to the base of the *Calocyclas talwani* Zone (Core 29, core catcher; RMG, pers. obs.), which coincides with a hiatus of long duration. A reliable age for the base of the *C. talwani* Zone cannot be determined on the basis of DSDP and ODP recovery. Goll (1989) placed the base of the *C. talwani* Zone at mid-Zone NP16 (of Martini 1971), and we conclude that the *P. duplus* Zone is correlative with the interval from upper Zone NP15 to lower Zone NP16. *P. duplus* has also been observed in Nordland Ridge well 6610/7-1 (RMG, pers. obs.).

Phacodiscus duplus differs from *P. 'postintricatus'* in its larger size and smooth-walled cortical lattice shell which is densely perforated by small, regularly spaced pores. Specimens of *P. duplus* in 7316/5-1 are invariably recrystallized, and the internal skeletal morphology cannot be determined. However, well-preserved specimens in the opal-A phase have been observed from the Vøring Plateau.

PHACODISCUS LENTICULARIS ZONE

Category: Interval zone.

Designation: BB-RD.

Definition: The top of the zone is taken at the lowest consistent occurrence of *Phacodiscus duplus*. The base of the zone is taken at the highest occurrence of *Sethodiscus microporus*.

Status: new.

Depth range: 1400–1490 m.

Material: Two samples from core 3 at 1465 and 1472 m, and 9 ditch cutting samples at 3–10 m intervals.

Age: Middle Eocene.

Equivalent zones: No clear equivalents on the Vøring Plateau.

Assemblage: *Phacodiscus lenticularis* has rare to abundant occurrences in this zone, but this species was not observed in the conventional core samples, which are essentially barren of radiolaria. Additionally, the species was not observed at 1375 m (dc) and 1380 m (dc). The rare occurrences of *Calocyclas talwanii* at 1432 m (dc) and 1442 m (dc) may be *in situ*, as the correct advent level of this species is unknown. The same is true of *Spongodiscus impressus*, which has four rare occurrences in the interval 1340 m (dc)–1480 m (dc). All other occurrences are regarded as displaced. These include five irregular rare occurrences of *Parvicingula* sp. in the interval 1320–1380 m and the rare occurrence of ?*Lithocyclia* sp. at 1432 m (dc), all of which are interpreted as being reworked. Caving artefacts include: common to abundant occurrences of *Phacodiscus* '*postintricatus*' throughout the zone; five rare–common occurrences of *Porodiscus* sp. A in the interval 1375 m (dc)–1450 m (dc); and three rare occurrences of ?*Spongotrochus glacialis* in the interval 1320 m (dc)–1380 m (dc) (Fig. 5).

Remarks: *Phacodiscus lenticularis* is the species referred to as *Cenosphaera* sp. by King (1989), and abundant occurrences of this taxa characterize the upper portion of Zone NSP 6. In the Barents Sea region, *P. lenticularis* clearly ranges in variable frequencies well above the top of Zone NSP 6, and abundant occurrences of this species in 7316/5-1 must represent a second younger acme, probably in Zone NSP 7. *P. lenticularis* has also been observed (RMG) in the lower Middle Eocene section of 7316/6-U-2.

The sponge *Geodia* has its lowest consistent occurrence (1442 m) in the *P. lenticularis* Zone. Specimens occurring in this zone, in the *Phacodiscus duplus* Kozlova 1966 Zone and the *Phacodiscus* '*postintricatus*' Zone are small with hollow centres, and are observable only under transmitted light.

SETHODISCUS MICROPORUS ZONE

Category: Total range zone.

Designation: BB-RE.

Definition: The top and base of the zone are taken at the highest and lowest occurrence of *Sethodiscus microporus*.

Status: new.

Depth range: 1490–1562 m.

Material: Eight ditch cutting samples at 10 m intervals.

Age: Middle Eocene (based on other biostratigraphical evidence).

Equivalent zones: No clear equivalents on the Vøring Plateau.

Assemblage: *Sethodiscus microporus* is common to abundant in all eight samples from this zone. Other specimens recorded as *Sethodiscus* sp. are poorly preserved, but may also belong to this species. Consequently, the *in situ* assemblage is regarded as monospecific. All other occurrences are interpreted as caving artefacts. These latter occurrences include: rare to common *Phacodiscus lenticularis* in the interval 1490–1552 m; rare to abundant *Phacodiscus* '*postintricatus*' in the interval 1490–1590 m; rare *Calocyclas talwani* and *Spongotrochus glacialis* sp. at 1490 m; and rare *Phacodiscus duplus* at 1490, 1512, and 1542 m (Fig. 5). Radiolaria are progressively more poorly preserved and less frequent with increasing depth.

UNZONED INTERVAL r2

Depth: 1562–1600 m.

Material: Five ditch cutting samples at 10 m interval.

Age: Middle Eocene (based on other biostratigraphical evidence).

Assemblage: Radiolaria are absent from this interval, with the exception of rare specimens of *Phacodiscus* '*postintricatus*' at 1572 and 1590 m, which are regarded as caved.

4.2 The outcrop at Balanusviken, Sarsbukta, western Spitsbergen

Feyling-Hanssen & Ulleberg (1984) described an 8-m-thick section of Oligocene micaceous claystone cropping out under glaciomarine overburden in a coastal cliff at Balanusviken, Sarsbukta, on the east side of Forlandsundet (Fig. 2). On the basis of the foraminiferal assemblages in seven samples, these authors divided the section into two zones: the overlying *Asterigerina gurichi* Zone (TB) and the underlying *Bolivina* cf. *antiqua* Zone (TA). Among a composite assemblage of 22 taxa for the entire section, Zone TA is distinguished by occurrences of the nominate species as well as *Gyroidina s. mamillata* and *Rotaliatina bulimoides*. Zone TB is distinguished by occurrences of the nominate species as well as *Angulogerina* *gracilis*, *A. tenuistriata*, *Pullenia quingueloba*, *Alabamina tangentialis* and *Epistominella oveyi*. Feyling-Hanssen & Ulleberg (1984) assigned a transitional Middle to Late Oligocene age to this entire section, and indicate an age equivalent to Subzones NSB 7a-NSB 8a according to King (1989).

Although the foraminiferal assemblage in Zone BB-FD of 7316/5-1 differs from that of the Balanusviken section in its generally lower diversity and poorer preservation, occurrences of *Turrilina alsatica*, *Angulogerina tenuistriata*, *E. pygmeus* and *Bolivina* cf. *antiqua* indicate a strong correlation.

New dinoflagellate cyst analyses are presented here for splits of two samples provided by Feyling-Hanssen & Ulleberg (sample 228 from Zone TB and sample 248 from Zone TA). The taxa identified in each sample are:

Sample 228: *Cribroperidinium giuseppei*, *Cordosphaeridium cantharellum*, *Deflandrea heterophlycta*, *Distatodinium paradoxum*, *Lentinia wetzelii*, *Palaeocystodinium* spp., *Phthanoperidinium comatum*, *Spiniferites ramosus*, *Spiniferites* sp. 2 (Manum et al. 1989), *Systematophora ancyrea* and *Systematophora placacantha*.

Sample 248: *Apteodinium* sp. 1, *Areosphaeridium arcuatum*, *Cometodinium* sp. 1, *Cribroperidinium giuseppei*, *Cordosphaeridium cantharellum*, *Cleistosphaeridium*? *insolitum*, *Deflandrea phosphoritica*, *Lejeunecysta hyalina*, *Spiniferites ramosus*, *Spiniferites pseudofurcatus*, *Systematophora ancyrea* and *Wetzeliella articulata*.

With the exceptions of *D. heterophlycta*, *Apteodinium* sp. 1, and *Cometodinium* sp. 1, all of the above taxa occur in the section at 7316/5-1. Extensive reworking of older Palaeogene taxa into Oligocene sediments is indicated at both localities.

The species, *C. giuseppei* and *W. articulata*, in sample 248 are normally indicative of an age not younger than the earliest Oligocene. Co-occurrences of *A. arcuatum* and *P. comatum* limit the assemblage to the range Middle Eocene to Lower Oligocene according to Manum et al. (1989) and Powell (1992). Although the stratigraphic ranges of *Systematophora placacantha*, *Cordosphaeridium cantharellum*, *Deflandrea phosphoritica* and *Spiniferites pseudofurcatus* extend above the Lower Oligocene, no dinoflagellates have been observed in the two samples from the Balanusviken section that provide conclusive

Table 1. Strontium isotope results from well 7316/5-1 and from Balanusviken at Forlandsundet on Spitsbergen. The $^{87}Sr/^{86}Sr$ ratio of the NBS 987 standard was 0.710240 ± 0.000011 during the sample analyses. Ages based on the time scales of both Berggren et al. (1985) and Cande & Kent (1995) are presented.

Sample ID	Well level	$^{87}Sr/^{86}Sr + 2$ sigma	Age (m.y.) (Berggren et al. 1985)	Age (m.y.) (Cande & Kent 1995)
7316/5-1				
A_1	987–1015 m	0.707791 ± 0.000011	ca. 35	32.8
A_2	987–1015 m	0.707795 ± 0.000008	ca. 35	32.8
B	1050–1070 m	0.707803 ± 0.000038	ca. 35	32.8
C_1	1472 m	0.707752 ± 0.000009	ca. 46–47	43.7–44.6
C_1	1472 m	0.707740 ± 0.000010	ca. 46–47	43.7–44.8
C_1	1472 m	0.707720 ± 0.000012	ca. 46–47	43.7–44.8
Fordlandsundet				
228M		0.708025 ± 0.000013	ca. 27.5	26.4
244M		0.707946 ± 0.000012	ca. 29.5	28.2
248M		0.707936 ± 0.000011	ca. 29.5	28.2
19M		0.707952 ± 0.000010	ca. 29.5	28.2

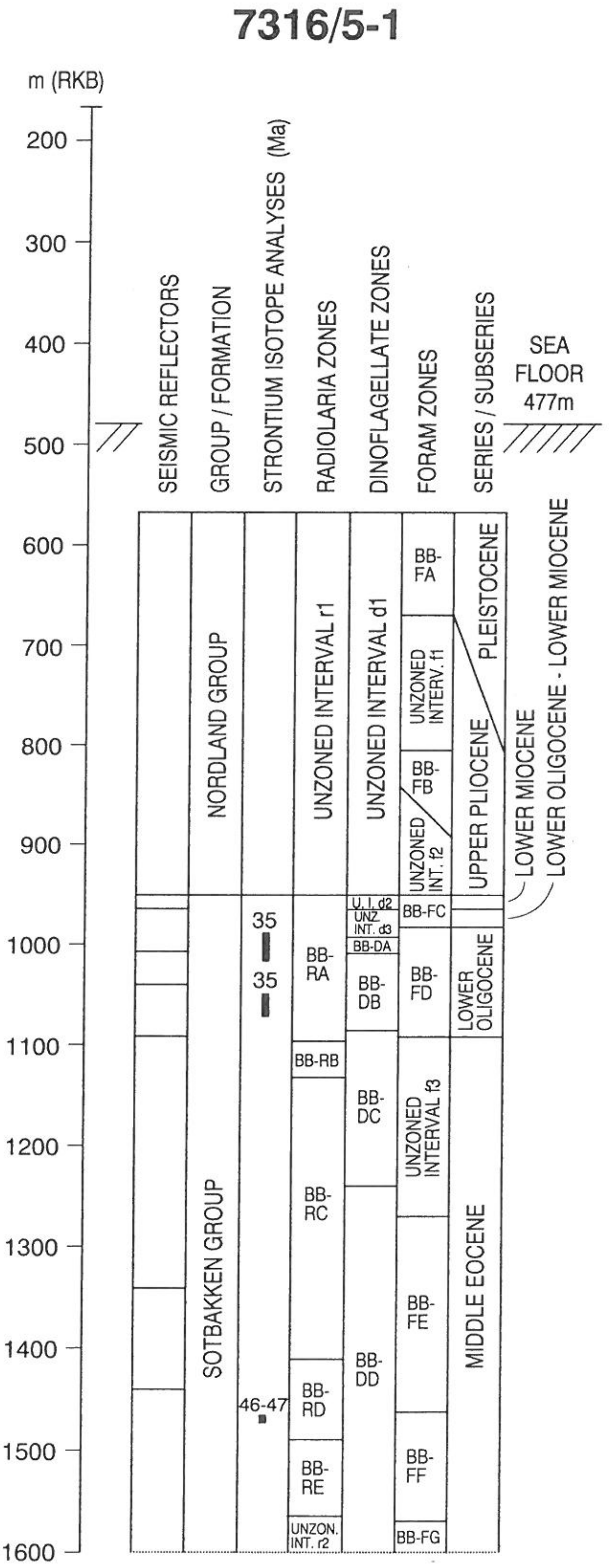

Fig. 7. Fossil zones, seismic reflectors, litostratigraphical groups, and levels investigated with strontium isotope analyses in well 7316/5-1.

evidence of a Late Oligocene or younger age. Based on the results of the strontium-isotope analyses described below, we conclude that most of the recovered specimens are reworked from Eocene and/or lowermost Oligocene deposits into the lowermost Upper Oligocene at this locality.

Manum & Throndsen (1986) proposed an age not younger than Late Eocene for the Balanusviken section based on the co-occurrence of *Cribroperidinium giuseppei*, *Kisselovia crassiramosa* and *Svalbardella cooksoniae*. Both *C. giuseppei* and *S. cooksoniae* occur in the Sotbakken Fm. of 7316/5-1 and are reported to range into the Lower Oligocene (Powell 1992). However, *K. crassiramosa* has a very restricted range in the Lower Eocene *Wetzeliella meckelfeldensis* Zone (Wme), according to Powell (1992), and the species has not been observed in the section at 7316/5-1. This apparently aberrant occurrence at the Balanusviken locality is here interpreted as the result of the extensive older Palaeogene reworking that is so evident at both localities.

5. Strontium-isotope results

Strontium-isotope analyses were conducted by the Institute for Energy Technology, Kjeller, Norway, on calcareous material (i.e. tests of calcareous benthonic foraminifera) from five samples representing three different stratigraphic levels in 7316/5-1 and four samples from the Forlandsundet section on Spitsbergen described by Feyling-Hanssen & Ulleberg (1984) (Table 1). In order to avoid problems with cavings and reworking, we analysed only stratigraphically diagnostic fossils. Ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$-ratio to a global strontium-isotope curve. The curve compiled by the Institute for Energy Technology, is based on data from DePaolo (1986), Depaolo & Ingram (1985), Hess et al. (1986), Hodell et al. (1989, 1990, 1991), Koepnick et al. (1985) and Palmer & Elderfield (1985). A curve for the Palaeogene based on data from well-dated strata in Denmark (Y. Rundberg, pers. comm. 1996) is also used.

Samples A_1 and A_2 were taken from the interval 987–1015 m. The closely similar Sr-ratios suggest the absence of contaminated or recycled material. The Sr isotope ratio of sample B is almost identical to those of samples A_1 and A_2 (Table 1), although sample B is from a stratigraphically lower horizon (foraminifera Zone BB-FD; 1050–1070 m). The strontium ratios of both these samples convert to an age of 35 Ma (i.e. Early Oligocene) on the basis of both the curve compiled by the Institute for Energy Technology and Y. Rundberg (pers. comm. 1996).

The similarity in the Sr-constitution between samples A_1-A_2 and B suggests that the relatively strong seismic reflector at 1040 m between these sample levels does not represent a hiatus of significant duration (Fig. 7).

Samples C_1-C_3 are from conventional core 3 at 1472 m. The very similar Sr-ratios correspond to an early Middle Eocene age of 46–47 Ma (Y. Rundberg, pers. comm. 1996).

All four samples analysed from the Balanusviken section on Spitsbergen indicate a Late Oligocene age. Samples 228 and 244 are from the TB Zone and samples 248 and 19 are from the TA Zone of Feyling-Hanssen & Ulleberg (1984) (Table 1). The $^{87}Sr/^{86}Sr$ ratios for samples 244, 248 and 19 are very similar and correspond to an age of 29.5 Ma. Sample 228 is from the top of the exposure, and its strontium ratio is equivalent to an age of 27.5 Ma.

6. Conclusions

6.1 Biostratigraphy and chronology

Pleistocene–Upper Pliocene (477–948 m). – The age of the clastic wedge of mainly glacigenic sediments recovered from between 477 and 948 m is basically determined by foraminifera. Foraminifera Zone BB-FA in 7316/5-1 corresponds to faunazone A in the wells 7117/9-1 and 7117/9-2 on the Senja Ridge, and 7119/7-1 in the Tromsø Basin (Eidvin et al. 1993), and is younger than 1.7 Ma. Foraminifera Zone BB-FB corresponds to faunazone D in 7117/9-1, and is of Late Pliocene age, but older than 2.3 Ma. Based on the high content of glacigenic material down to 948 m and correlation to the Vøring Plateau (Jansen & Sjøholm 1991; Jansen 1995), a maximum age of 2.6 Ma is assigned to the oldest Pliocene deposits in 7316/5-1.

Lower Miocene (948–960 m). – Sediments of Early Miocene age are sampled only at 950 m and 960 m. The foraminifera indicate only a general Early Miocene to Oligocene age for this interval, but the recovered dinoflagellates restrict these sediments to the Lower Miocene. There is a marked lithological and seismic boundary between this and the overlying unit. Lower Miocene sediments have previously not been reported from any exploration well on the western Barents shelf, but sediments of this age were recovered in the shallow borehole 7316/06-U-01 just east of well 7316/5-1 (Sættem et al. 1994).

Lower Miocene–Lower Oligocene (960–982 m). – The recovered *in situ* foraminifera and dinoflagellates indicate only a general Early Miocene to Oligocene age for this interval, and there is only a weak indication that some of the radiolaria are of Early Oligocene age.

Lower Oligocene (982–1090 m). – Foraminifera attributed to the *Turrilina alsatica-Angulogerina tenuistriata* Zone (BB-FD) and dinoflagellates attributed to Zones BB-DA and BB-DB, together with strontium-isotope ages obtained from 987–1015 m and 1050–1070 m, date this interval to the Early Oligocene.

It is possible that the uppermost part of this section and the overlying section are a condensed (Upper) Oligocene sequence; an interpretation that is supported by the seismic profile. However, this interpretation is not evident from the biostratigraphic data.

The base of this unit coincides with a strong seismic reflection, representing a major regional sequence boundary.

Middle Eocene (1090–1600 m, lowest studied sample level). – With the exception of the foraminifera in the Unzoned Interval f3, all the fossil groups obtained from this unit suggest a Middle Eocene age. Strontium isotope ages obtained at 1472 m give an age of 46–47 Ma, supporting the age determinations based on the microfossils and palynomorphs.

6.2 Palaeoenvironments

Pleistocene–Upper Pliocene. – Almost all samples from the Pleistocene–Upper Pliocene sequence in 7316/5-1 contain glacigenic material. The recovered microfossil and palynomorph assemblages consist dominantly (foraminifera) or almost exclusively (dinoflagellates) of recycled specimens, and the radiolaria fauna in this sequence contains only reworked forms. *In situ* foraminifera have been found in faunasones BB-FA and BB-FB, but between these zones and below faunazone BB-FB there are indeterminant intervals of almost exclusively redeposited forms.

Foraminifera Zone BB-FA is fairly rich in calcareous forms, amongst which the planktonic comprise a significant part. A large proportion of planktonic foraminifera in coastal areas indicate open marine and fairly deep water conditions. The significant concentration of *B. marginata* and common occurrence of *N. affine* also indicate fairly large water depths (Qvale & van Weering 1985; Mackensen et al. 1985). The unit comprising Zone BB-FA was probably deposited in an outer shelf environment. The content of polar species such as *E. excavatum* forma *clavata*, *C. reniforme*, *I. islandica*, *I. norcrossi*, *N. labradoricum*, and the complete dominance of *N. pachyderma* (sinistral) in the planktonic fauna indicate cold water conditions (Feyling-Hanssen 1983).

The Unzoned Interval f1 contains only sporadic calcareous foraminifera. The Pleistocene–Upper Pliocene sediments further to the south on the Norwegian shelf are, however, rich in calcareous forms. The absence of calcareous forms in this interval is probably due to carbonate dissolution. According to Hald et al. (1989) and Steinsund et al. (1991) dissolution of calcareous foraminifera follows the pattern of formation of heavy bottom water, created by the combination of sea ice and the influx of Atlantic water masses. The water becomes corrosive to $CaCO_3$ due to excess CO_2 from decomposition of organic matter on the shelf. The combination of low temperature and high salinity may explain this phenomenon in Recent and Upper Pleistocene deposits (Hald et al. 1989). This is probably also the case for the older Pleistocene and the Upper Pliocene sediments.

Foraminifera Zone BB-FB also contains some calcareous foraminifera, although fewer than in Zone BB-FA. This relatively low ratio of calcareous tests may also be attributed to carbonate dissolution. This possible selective dissolution of some tests impedes environmental interpretation due to the limited number of specimens. There are apparently fewer arctic forms compared to boreal species in Zone BB-FB. The content of planktonic foraminifera, and the presence of the benthonic species *N. affine*, *C. teretis* and *B. margarita* indicate open marine conditions and deposition at a water depth corresponding to the middle shelf or deeper.

The lower part of the Pleistocene–Upper Pliocene sequence (i.e. Unzoned Interval f2) is almost barren of calcareous for aminifera. As in the overlying Pleistocene–Upper Pliocene units most of the samples from this zone comprise a diamicton probably of mainly glaciomarine origin. In the middle part of this unit a cored sand unit is interpreted as a glaciofluvial meltwater delta. This indicates a fairly shallow environment for these sediments in the middle part of the unit.

Lower Miocene–Lower Oligocene. – Recycled microfossils and palynomorphs are common to dominant in the Miocene and Oligocene sequences of 7316/5-1.

In the Lower Miocene sequence the *in situ* occurrence of the dinoflagellate genera *Spiniferites*, *Systematophora*, *Invertocysta*, *Hystrichosphaeropsis*, together with *Impagidinium*, indicates an open marine environment and possible deposition on the middle to outer shelf. The occurrence of *Impagidinium*, *Systematophora* and *Spiniferites* in the Early Oligocene Zone BB-DA, and the occurrence of *Areosphaeridium*, *Spiniferites* and *Systematophora* in the Early Oligocene dinoflagellate Zone BB-DB, indicate similar depositional environments for these units.

The presence of only agglutinated foraminifera in Fauna Zone BB-FC indicates low oxic to dysoxic bottom conditions and the dissolution of any calcareous forms. According to Skarbø & Verdenius (1986), the presence of *R. placenta* indicates fairly deep water. The lack of planktonic foraminifera in the Early Oligocene Zone BB-FD suggests a restricted connection with the open ocean during the deposition of this unit. The benthonic fauna, however, contain forms associated with fairly deep water (i.e. *Bolivina* cf. *antiqua* and *Gyroidina s. girardana*), and also species linked to fairly shallow water depths (*T. alsatica* and *C. aknerianus*) (Skarbø & Verdenius 1986). Christensen & Ulleberg (1974) and Ulleberg (1985) described typical shelf faunas of benthonic calcareous foraminifera from Oligocene deposits in Denmark, with many of the species also recorded here. The previously mentioned Oligocene fauna from Forlandsundet (Spitsbergen) is also characterized as a typical shelf fauna. In conclusion, the foraminifera indicate deposition on the middle to outer shelf for the sediments comprising Zone BB-FC, and the middle part of the continental shelf for Zone BB-FD in 7316/5-1.

Middle Eocene. – The dinoflagellate floras are rich and fairly diverse in the Middle Eocene sequence. With the exception of the cored sand intervals between 1347.5–1374.4 m and 1460.5–1472 m, and in Zone BB-RE, radiolaria are also common in this unit. There is also a fairly rich foraminifera fauna, except in the Unzoned Interval f3 in the upper part of the Middle Eocene sequence. In Zone BB-FE agglutinated forms dominate, but a minor proportion of planktonic and benthonic calcareous forms also occur. In Zone BB-FF there is a fairly rich fauna of both agglutinated, calcareous benthonic and planktonic species, although the calcareous benthonic taxa are most common. Only agglutinated forms are recovered from Zone BB-FG.

The large concentration of radiolaria, which is generally associated with normal marine conditions with little water turbulence, indicates that much of the Middle Eocene sequence was deposited in relatively deep open marine environment. This interpretation is supported by the planktonic foraminifera in Zones BB-FE and BB-FF. Exceptions are the sand intervals mentioned above and the beds comprising radiolaria Zone BB-RE. The upper sand interval is interpreted as a shallow water deposit, while the lower is interpreted to represent turbidites. The sand layers contain few or no microfossils. Possible microfossils were probably winnowed from these high-energy deposits. However, within the turbiditic sand unit there are thin fine-grained layers which contain common microfossils. The benthonic foraminiferal taxa found throughout much of the Middle Eocene sequence are also indicative of fairly deep water conditions (Skarbø & Verdenius 1986).

The wide diversity of dinoflagellates, including the occurrence of *Areosphaeridium*, *Spiniferites*, *Systematophora* and *Hystrichokolpoma* (Zone BB-DD), indicates an open marine depositional environment. The fairly common occurrence of *Glaphyrocysta* and *Nummus* in the middle Zone BB-DD may indicate a somewhat more marginal marine setting for these sediments.

An outer to middle shelf environment is suggested for the Middle Eocene sequence; however, the upper sandy unit is thought to have been deposited in a significantly shallower marine environment. Low oxygen content may explain the paucity or absence of calcareous foraminifera in certain sections of the sequence.

6.3 Tectonic history and geological evolution

The Vestbakken volcanic province (Gabrielsen et al. 1990) is identified by a complex of acoustically opaque and high amplitude reflectors interpreted to originate from volcanic sequences. Prior to drilling of the well, the Early Eocene age for these rocks was correctly predicted by Eldholm et al. (1987), and interpreted as lava swarms and intrusives formed during the early stages of opening of the Norwegian–Greenland Sea. They interpreted the basin as lying above a thinned continental crust developed as part of a transtensional ('leaky transform') component of the regional early Tertiary dextral shear system which formed part of the progressive northward opening of the ocean basin (Faleide et al. 1988; 1996). The 'leaky transform' formed as the relative plate motion acted at an oblique angle to the curved incipient plate boundary as defined by older lineaments along which the opening was initiated (i.e. the Knølegga Fault and its associated subparallel feature, the 'eastern boundary fault') (Fig. 1).

Based on datings in well 7316/5-1 and the observed seismic correlation (this paper), the local geological evolution of the area may be summarized in seven stages as follows:

Stage 1 (Early–Middle Eocene)

After cessation of the volcanic and intrusive activity in the Early to Middle Eocene, the basin west of the 'eastern boundary fault' subsided rapidly, probably receiving predominantly fine-grained sediments from easterly provenance areas. It is possible that sediments at the well location represent the relatively distal facies of prograding wedges built out from the Knølegga and eastern boundary fault escarpments. There is some evidence of synsedimentary faulting possibly resulting from tectonically induced dewatering within this sequence. Two sandstone units (one interpreted to be of shallow marine origin; the other a slumped turbidite) are recorded in the upper part of the penetrated Middle Eocene sequence, perhaps reflecting increasing proximity to the sediment source area and/or greater activity along the fault systems.

The rapid thermal subsidence of local subbasins during the Middle Eocene is consistent with the interpreted stepwise northeasterly progradation of the spreading rift axis from Anomaly 24 time (ca. 55 Ma), and appears to have continued into the Oligocene (until Anomaly 13 time, 37–36 Ma). It is during this period that the 'leaky transform' model is most applicable.

Stage 2 (Late Middle Eocene–earliest Oligocene)

Upper Middle and Upper Eocene sediments, together with those of earliest Oligocene age, are absent in the well. East of the well location the hiatus is expressed as a subtle angular unconformity truncating older Middle Eocene sequences. It is not anticipated that this represents a period of major regional tectonism, rather that transpressive movements developed along the eastern boundary fault causing uplift and inversion of the downthrown flank. However, movements of this age are observed in the Vøring Basin, (H. Brekke, pers. comm. 1995), suggesting that there may also be a regional component. The sediments were consequently raised above the wave base, resulting in a period of mild erosion and non-deposition. This appears to have occurred in the period between 45 and 34 Ma, to some extent pre-dating, but also overlapping, the supposed initiation of the northwesterly direction of relative plate motion in the Norwegian–Greenland Sea (Anomaly 13 time, 37–36 Ma).

Stage 3 (Early Oligocene)

The Early Oligocene appears locally to have been a period of gentle subsidence accompanied by westerly tilting of the subbasin. East of the well location, intra-Oligocene reflectors appear to onlap the basal Oligocene unconformity from the west, and there is little or no evidence on seismic of significant sediment transport from the east.

Stage 4 (Late Oligocene–Early Miocene)

Upper Oligocene sediments are not proved in the well. There is no distinct hiatus or unconformity recorded locally on seismic at this level, and it is suggested that the sequence is severely condensed. This appears to have resulted from concurrent initial updoming and extensional faulting of the present PL 184-antiform, and subsidence along the downthrown flank of the 'eastern boundary fault'. It is, therefore, likely that an expanded sequence of Oligocene and Lower Miocene sediments was deposited and is now preserved in the eastern depression.

Gentle subsidence in the Early Oligocene (?34–30 Ma) was followed by a combination of reactivation of the Knølegga and its associated fault systems, and local differential subsidence during the Late Oligocene and Early Miocene (30–?20 Ma). At this time sea-floor spreading activity would have been well established to the west of the PL 184 area, promoting sedimentation in locally developed open marine basins formed between highs generated by the continuing structural readjustments to the new tectonic regime. A global eustatic lowering of sea level resulting from the initiation of the Antarctic glaciations (Vågnes et al. 1992) may also have exerted an influence in condensing Oligocene sequences, although it is not possible to quantify the relative magnitude of these events.

Stage 5 (Middle–Late Miocene)

The presence of a major intra-Lower Miocene sequence boundary in the well may be an indication of transgression across the high at this time. An interpretation of further Miocene sedimentation across the study area must remain speculative, although it is clear that stable deposition continued in the eastern depression and that regional depositional patterns appear to have involved an eastward migration of the shelf edge (as indicated by the shallow well 7316/6-U-1, Sættem et al. 1994). Two interpretations may be considered; either the PL 184 structure continued to form during the Middle to Late Miocene, resulting in a condensed sequence now removed from the high. The observed reactivation of some Oligocene faults may be cited as evidence of this, although the faulting may have occurred as late as Middle to Late Pliocene. In addition, doming due to transpression along older faults in Middle to Late Miocene times is also observed in the Vøring Basin (H. Brekke, pers. comm. 1995). Alternatively, subsidence and deposition may have developed regionally across the entire subbasin depositing approximately 500 m or more of sediments, also now removed by erosion.

Stage 6 (Miocene to Pliocene)

At some stage during the Middle to Late Miocene or Early to Middle Pliocene there was a net regional uplift of the Vestbakken province (presumably together with much of the present western Barents Sea area), accompanied by limited local reactivation of some of the Oligocene faults on the PL 184 structure. Easterly tilting was facilitated by subsidence of the hanging wall along the 'eastern boundary fault'. The precise regional background for this tectonic event (or events) is unclear, although thermal uplift associated with accelerated sea-floor spreading, together with glacio-isostatic tectonic cycles, may have been driving mechanisms. Evidence for local volcanic activity of Pliocene age (2–3 Ma) is recorded in shallow well 7316/3-U-1 (Mørk & Duncan 1993), and may lend support to the argument for a thermal component.

Stage 7 (Late Pliocene–Pleistocene)

Upper Pliocene glacial sediments rest unconformably on eroded Lower Miocene sediments at the well location. On seismic the unconformity dips at ca. 1.5° towards the west across the licence area. In the east this surface divides a younger from an older wedge of similar seismic character, the latter also resting unconformably on supposed Miocene sediments. The older wedge is not observed at the well location. Towards the west the younger unconformity erodes as deep as the equivalent of the Lower Oligocene sequence recorded in the well. That the present unconformity truncates progressively older sediments towards the west would suggest that the Stage 6 uplift involved an easterly tilt component, aided by reactivated movement along the hanging wall of the 'eastern boundary fault', assuming that the surface was originally flat.

Since the initiation of cyclic progradation of the Plio-Pleistocene wedges on the unconformity surface, westerly tilting has progressively reverted the PL 184 structure to its present position. Evidence for this is seen in the configuration of younger sequence boundaries within the main wedge, which itself has been eroded by at least two recent and distinct Quaternary erosional cycles seen as unconformities on seismic. This has been in part controlled by relative subsidence of the newly formed oceanic crust, enhanced by recent isostatic rebound of previously glaciated sediment source areas to the east. Earlier generations of similar wedges have undoubtedly been successively reworked by more intense cycles of glacially related sediment transport and deposition.

7. Discussion

The ages of the thick Cenozoic fan deposits on the western margin of the Barents Shelf have been difficult to assign, and major uncertainties were inherent in the earlier dating of the fans. Unpublished consultant reports proposed an Eocene age for the lower part of the wedge, leading Spencer et al. (1984) to conclude that the base of the sedimentary wedge (i.e. their Unit III A) is a major hiatus. Ages of the deposits above this hiatus ranged from Miocene to Late Pliocene in age, which led some authors to propose an intra-Oligocene age for the boundary (i.e. Nøttvedt et al. 1988; Vorren et al. 1990). Vorren et al. (1991) proposed that the lower unit of the wedge is of Middle to Late Miocene age, based on downlap on oceanic crust and magnetic anomalies. A similar age interpretation was used by Richardsen et al. (1993) and Knutsen et al. (1993) in their seismic stratigraphic studies of the wedge. The redating of wells on the Senja Ridge (Eidvin & Riis 1989; Eidvin et al. 1993) has provided evidence that the thick sedimentary wedge was built over a relatively short time period in the Late Pliocene–Pleistocene, mainly as a result of glacial erosion of the Barents Shelf region. Based on studies of shallow cores in the Bjørnøya West area, Sættem et al. (1992, 1994) and Mørk & Duncan (1993) also concluded that the base of the wedge is of Late Pliocene age.

The sediments directly overlying the seismic reflector at the base of unit B, as defined by Sættem et al. (1992), is younger than 0.73 Ma, according to palaeomagnetic studies of borehole 7317/10-U-01 (Fig. 2). Two ^{40}Ar/^{39}Ar isotopic ages of 2.34 and 2.20 ±0.12 Ma respectively have been obtained from volcanic ash in borehole 7316/03-U-01 (Fig. 2). This delineates the base of the fan (base of unit A_0 of Sættem (1992)), (Mørk & Duncan 1993; Sættem et al. 1994). Based on lithologic correlations with ODP holes in the Norwegian Sea that have been investigated by Jansen & Sjøholm (1991) and Jansen (1995), the base of the fan in both the Senja Ridge wells (Eidvin et al. 1993) and well 7316/5-1 are believed to be no older than 2.6 Ma. However, a minimum age of 2.3 Ma for the sediments at the base of the fan (Assemblage Zone D of Eidvin et al. (1993), and Assemblage Zone BB-FB of 7316/5-1) is inferred on the basis of biostratigraphic correlations with the same ODP holes. These considerations suggest that the oldest ^{40}Ar/^{39}Ar age within the maximum margin of error is probably most correct. ODP Hole 986 is situated on the continental slope west of Spitsbergen and penetrated the entire fan section (Fig. 2). Palaeomagnetic and biostratigraphic studies of this hole presently undertaken will provide a much more accurate chronology of fan development in the late Pliocene.

Ages based on the strontium-isotope compositions of foraminiferal tests from the Oligocene sequences in borehole 7316/5-1 and the outcrop at Forlandsundet, Svalbard indicate that the relatively similar faunas have an age difference of 5–6 m.y. Chronologic correlations supported by strontium-isotopic ratios are significantly more accurate than traditional biostratigraphic methods for such sequences. Sea-water strontium ages of 27.5–29.5 Ma support the interpretation of Feyling-Hanssen & Ulleberg (1984) that the sequences are early Late Oligocene in age. A Late Eocene age for the outcrop at Forlandsundet based on dinoflagellate correlations (Manum & Throndsen 1986) was based on redeposited specimens, as is evident from the dinoflagellate investigation of samples from this sequence in the present study.

Acknowledgements. – The authors acknowledge Norsk Hydro a.s. for access to data and permission to publish, and extend their thanks to Bjørg Ruus, Sigrun Torrissen and Finn Moe for their careful and accurate technical assistance during this project. They also thank Robert Williams, Fridtjof Riis, Astrid Larsen, Jenö Nagy, Bruce A. Tocher, Gøran Åberg and Helge Stray for their cooperation. Eystein Jansen, Gunn Mangerud and Sven Manum reviewed the manuscipt and offered numerous suggestions.

Manuscript received May 1996

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Paper 7:
Foraminifer biostratigraphy of Pliocene deposits at Site 986, Svalbard Margin

Raymo, M.E., Jansen, E., Blum, P., and Herbert, T.D. (Eds.), 1999
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 162

1. FORAMINIFERAL BIOSTRATIGRAPHY OF PLIOCENE DEPOSITS AT SITE 986, SVALBARD MARGIN[1]

Tor Eidvin[2] and Jenö Nagy[3]

ABSTRACT

The upper Pliocene interval from 647.72 through 955.32 meters below seafloor in Ocean Drilling Program Hole 986D (77°20.408′N, 9°04.654′E) can be subdivided into one planktonic foraminiferal zone: nominate species, *Neogloboquadrina atlantica* (sinistral); one calcareous benthic foraminiferal zone: nominate species, *Melonis zaandamae–Cassidulina teretis*; and four agglutinated foraminifer assemblages: AFA1 through AFA4. The whole interval was deposited between 2.6 and 2.4 Ma during a climatic regime comprising episodic ingressions of warm to transitional surface-water masses into a generally cold ocean. Broken calcareous benthic foraminifers and silicified deformed agglutinated foraminifers indicate considerable reworking. The planktonic and calcareous benthic assemblages are similar to faunas in Hole 910C on the Yermak Plateau (80°15.896′N, 6°35.430′E), Hole 643A on the Vøring Plateau (67°42.9′N, 01°02.0′E), and the exploration Wells 7117/9-1 and 7316/5-1 on the Senja Ridge (71°22′51.05″N, 17°56′5.76″E) and in the Vestbakken Volcanic Province (73°31′12.78″N, 16°25′55.87″E), respectively. The lowermost 55 m of the interval was probably deposited below the local carbonate compensation depth and contains only agglutinated foraminifers.

INTRODUCTION

Along the margins of the Norwegian-Greenland Sea, three main glaciation areas produced extensive ice sheets in Pliocene–Pleistocene times: Greenland, Scandinavia, and the Svalbard-Barents Sea. Site 986 was drilled on the Svalbard Margin (Fig. 1) to establish the history of the Svalbard-Barents Sea Ice Sheet, including the timing of the onset of glaciation, the shift of glaciation style from mountain to ice-sheet type, and the extension of marine-based ice sheets to the outer shelf. Four holes were drilled at Site 986, with a maximum penetration of 964.6 meters below seafloor (mbsf) in Hole 986D. The drilled section penetrates all the main regional reflectors (R1–R7) of the Svalbard-Barents Sea Margin, and there are strong ties between the reflectors and main seismic sequences shown by core physical property measurements and wireline logging (Jansen, Raymo, Blum, et al., 1996). The samples analyzed for foraminifers in this study are from the upper Pliocene interval 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 60R-1, 29–36 cm (955.32 mbsf; 77°20.408′N, 9°04.654′E) (Fig. 2). The seafloor lies at 2063 meters below rig floor.

In the foraminiferal assemblages, an in situ and a redeposited component are distinguished, mainly based on the state of preservation. The in situ component includes both planktonic and benthic taxa, which are used for stratigraphic dating and correlation combined with magnetostratigraphic data. All absolute ages are based on Berggren et al. (1995).

In late Cenozoic time, the western margin of the Barents Shelf was an area of intensive sediment influx from a drainage area of more than 1 million km^2 covering most of the Svalbard-Barents Sea platform. As a result of this influx, extensive Pliocene–Pleistocene sediment wedges were deposited along the continental margin. Site 986 is located on the lower continental slope, on the northern extension of the sediment wedge developed in front (west) of the Storfjorden Trough. In the analyzed interval, the distribution pattern of the three main components of foraminiferal assemblages (the agglutinated, calcareous benthic, and planktonic groups) and the occurrence of the lower taxa (genera and species) support the interpretation of mass-wasting and redeposition processes acting on the continental slope of this region.

METHODS

The stratigraphy of the upper Pliocene succession at Site 986 was established by the investigation of planktonic, calcareous benthic, and agglutinated benthic foraminifers from 131 samples. Approximately one 30-cm^3 sample per section of core was used. The samples were disaggregated with water without dispersant. Samples were soaked in water overnight and then mechanically agitated before washing over a 63-µm sieve. The residue was then dried overnight in an oven at <60°C. The fossil identifications were carried out in the 106- to 500-µm fraction. In some samples, the fractions <106 µm and >500 µm were also investigated. Whenever possible, 300 individuals were picked from each sample. In order to better identify the microfossil assemblages, a number of samples rich in mineral grains were also gravity separated in tetrachloroethylene.

LITHOSTRATIGRAPHY

The investigated interval from Sample 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 45R-7, 29–36 cm (820.02 mbsf), belongs to lithologic Unit III (Figs. 3–6). This unit is characterized by a relatively high sand content and the absence of dropstones. The primary lithologies are very dark gray to dark greenish gray silty clay with sand, clayey silt with sand, silty clay, and sandy silty clay. Biogenic calcareous sediment is present in trace to minor amounts throughout the unit. The biocarbonate consists largely of calcareous nannofossils in amounts up to 20% (by volume) and shows a slight increase downcore. Authigenic iron sulfides, primarily in the form of disseminated pyrite, are commonly present in minor amounts (Jansen, Raymo, Blum, et al., 1996).

The section from Sample 162-986D-46R-1, 29–36 cm (820.59 mbsf), to the base (60R-1, 29–36 cm, 955.32 mbsf) belongs to lithologic Unit IV (Figs. 3–6). The transition from Unit III to Unit IV is

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[1] Raymo, M.E., Jansen, E., Blum, P., and Herbert, T.D. (Eds.), 1999. *Proc. ODP, Sci. Results,* 162: College Station, TX (Ocean Drilling Program).

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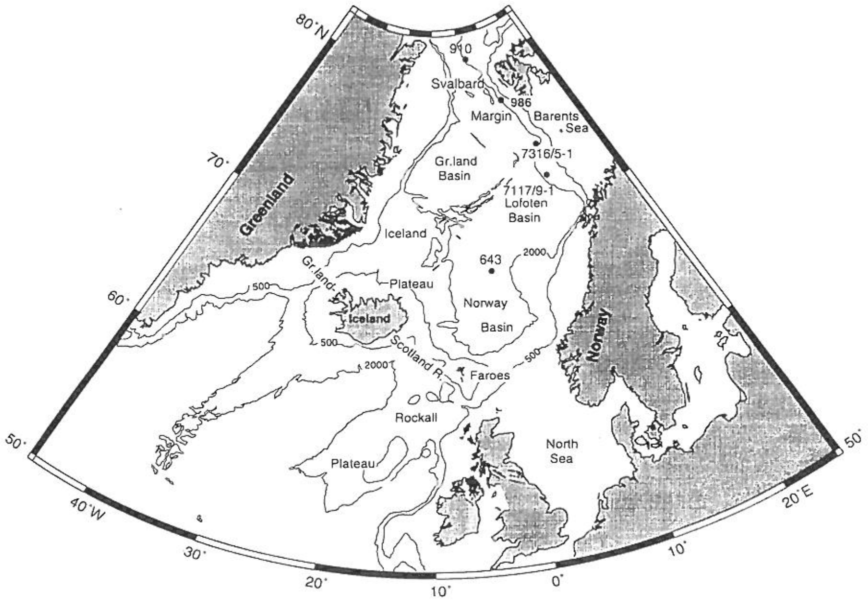

Figure 1. Map of the North Atlantic showing position in the Norwegian-Greenland Sea of sections discussed.

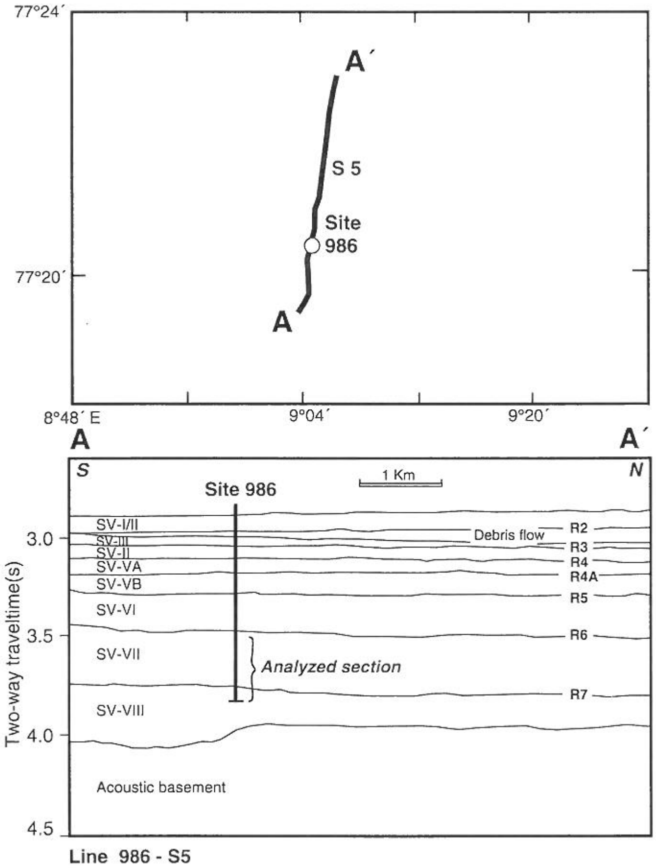

Figure 2. Position of the borehole interval analyzed geographically and in relation to reflectors in a seismic section (A–A′). After Jansen, Raymo, Blum, et al. (1996).

marked by a decrease in sand- and silt-sized components. Subunit IVA (820.0–895.42 mbsf) is distinguished from the underlying sediments by increased magnetic susceptibility values and higher sand content. The sediments are predominantly composed of dark gray to black silty clay, with minor amounts of dark gray to black silty sand. Biocarbonate is present in minor amounts within this subunit (average 2.8%). Subunit IVB (897.62–955.32 mbsf) is distinguished from the overlying sediments by very low magnetic susceptibility values, a further decrease in sand content, and by the absence of biocarbonates. Subunit IVB is entirely composed of very dark to black silty clay. Silt- and sand-sized mineral components are less abundant than in Subunit IVA (Jansen, Raymo, Blum, et al., 1996).

PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY

The high-latitude planktonic foraminiferal associations are low-diversity faunas composed of long-ranging species. In general, it is not possible to apply the standard zonations established for low latitudes (Blow, 1969, 1979; Bolli and Saunders, 1985) or for northern temperate regions (Berggren, 1972; Poore and Berggren, 1975; Poore, 1979; Weaver and Clement, 1986) because the index fossils used for these zonal definitions are often absent in high-latitude assemblages. Studies of Ocean Drilling Program (ODP) Leg 104 sites on the Vøring Plateau in the Norwegian Sea have produced a local high-latitude Neogene zonation (Spiegler and Jansen, 1989; Spiegler, 1996) that is useful for comparison with Site 986. Data from ODP Leg 151 sites from the Fram Strait and the Yermak Plateau are also applicable (Spiegler, 1996).

Planktonic foraminifers are found in 80% of the samples in the interval from Sample 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 54R-1, 29–36 cm (897.62 mbsf). The interval from 897.62 mbsf to the base of the drilled succession (Sample 162-986D-60R-1, 29–36 cm, 955.32 mbsf) is barren of planktonic foraminifers. In the 250-m-thick interval containing planktonic foraminifers, the assemblage exhibits highly variable abundance, fluctuating from rich faunas to intervals that are poor in or barren of planktonic foraminifers. Except in a few samples, most specimens are well preserved and show no signs of reworking.

The assemblage consists mainly of *Neogloboquadrina atlantica* (sinistral) and *Globigerina bulloides*. *N. atlantica* (dextral) occurs sporadically, mainly in the upper part of the section. *Neogloboquadrina pachyderma* (sin., mainly unencrusted form), *N. pachyderma* (dex.), *Turborotalita quinqueloba*, and *Globigerinita glutinata* occur in small numbers in some intervals throughout the succession (Fig. 3).

In the high-latitude Neogene, *N. atlantica* (sin.) is indicative of the *Neogloboquadrina atlantica* (sin.) Zone, spanning Pliocene to latest Miocene age (Spiegler and Jansen, 1989). The entire carbonate-

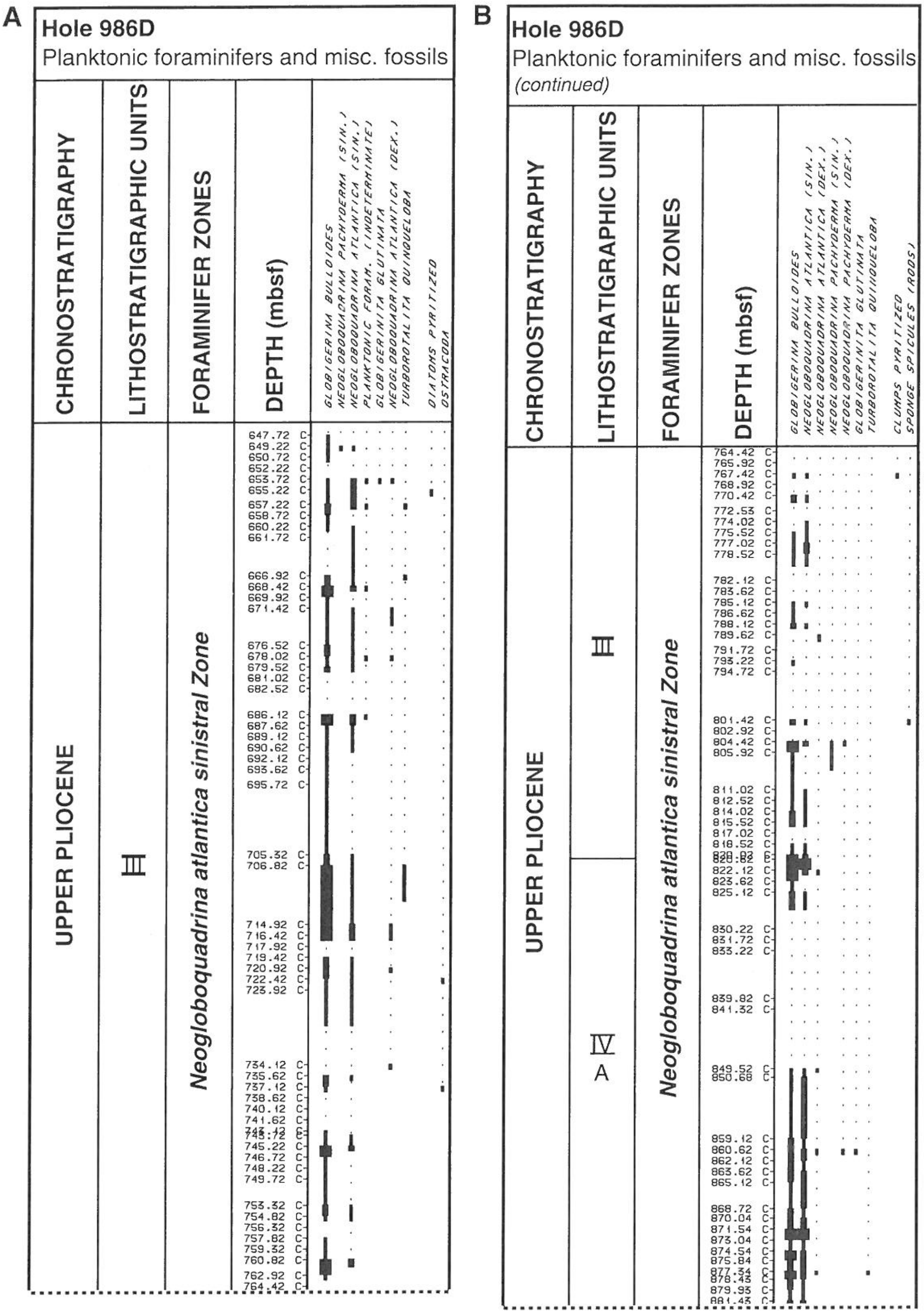

Figure 3. **A.** Range chart of upper Pliocene planktonic foraminifers and miscellaneous fossils in Hole 986D (upper part of investigated section). In the bar chart, a thin bar = <10 specimens, a medium bar = 10 to 30 specimens, and a thick bar = >30 specimens. C = core sample. **B.** Range chart of upper Pliocene planktonic foraminifers and miscellaneous fossils in Hole 986D (middle part of investigated section). (Continued on next page.)

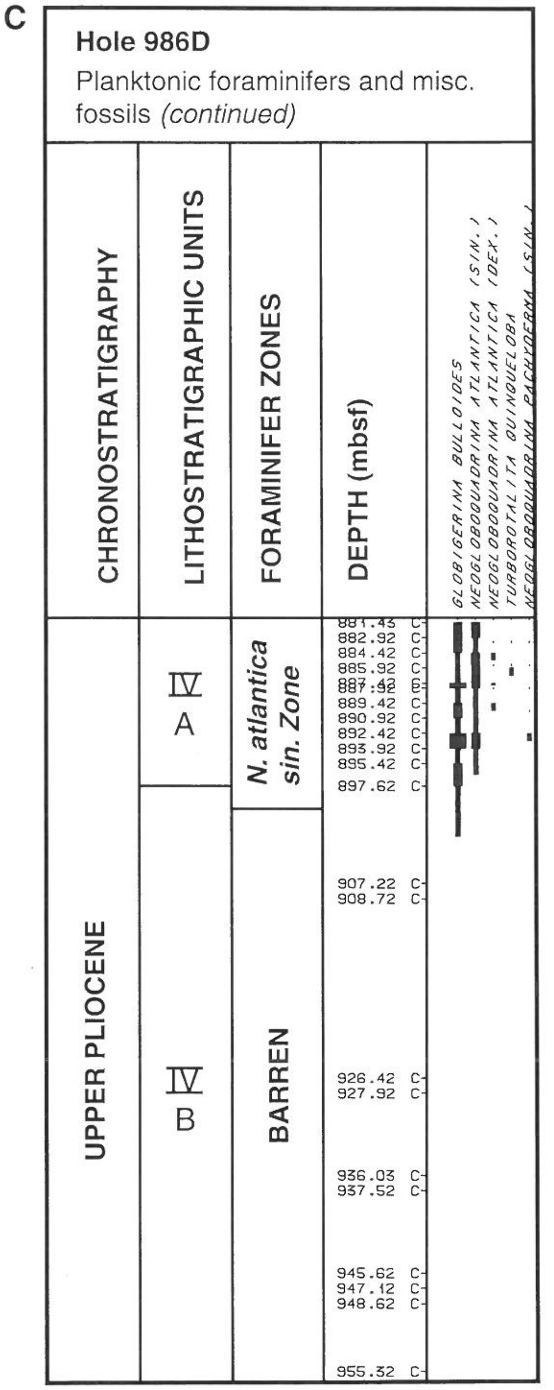

Figure 3 (continued). **C.** Range chart of upper Pliocene planktonic foraminifers and miscellaneous fossils in Hole 986D (lower part of investigated section).

bearing sequence is assigned to the *N. atlantica* (sin.) Zone. This zone is also rich in *G. bulloides*. On the Vøring Plateau and in the North Atlantic, the last occurrence (LO) of *N. atlantica* (sin.) is no younger than 2.4 Ma (Weaver and Clement, 1986; Spiegler and Jansen, 1989; Channell and Lehman, Chap. 8, this volume). The LO of *N. atlantica* (dex.) is close to the Pleistocene/Pliocene boundary (Weaver and Clement, 1986; Spiegler and Jansen, 1989). This species occurs sporadically in the *N. atlantica* (sin.) Zone of Spiegler and Jansen (1989).

Paleomagnetic data in Hole 986D show that the base of the core is in the Matuyama Chron, which implies an age of <2.6 Ma (Channell et al., Chap. 10, this volume). The calcareous benthic foraminifer *Cibicides grossus* occurs down to 877.34 mbsf. This also indicates a late Pliocene age for this interval.

The climatic regime in this area during the late Pliocene may be interpreted to comprise episodic ingressions of warm and transitional surface-water masses into a generally cold ocean. The occurrence of *N. pachyderma* (dex.), *T. quinqueloba*, and *G. glutinata* indicates several short, warm to transitional surface-water events. The cold conditions are documented by *N. atlantica* (sin.) and *N. pachyderma* (sin.) (Spiegler, 1996). The highly variable abundance of planktonic foraminifers seems also to be typical of alternating glacial and interglacial conditions. At high northern latitudes, planktonic foraminifers are generally less common as a result of low water temperatures and/or dissolution of the calcareous microfossils. Another reducing factor is dilution by large amounts of detrital material and ice-rafted debris (Spiegler, 1996).

CALCAREOUS BENTHIC FORAMINIFERAL BIOSTRATIGRAPHY

Upper Pliocene calcareous benthic foraminifers are described from open-ocean high-latitude areas at ODP Sites 642, 643, and 644 on the Vøring Plateau (Leg 104; Osterman and Qvale, 1989) and Site 910 on the Yermak Plateau (Leg 151; Osterman, 1996). Paleomagnetic records from these boreholes provide good age control for the fossil zones. Upper Pliocene calcareous benthic foraminiferal assemblages are described from outer-shelf sites in exploration wells on the Senja Ridge (Eidvin et al., 1993a) and in the Vestbakken Volcanic Province (Eidvin et al., 1998b) in the western Barents Sea (Fig. 1). In the Vestbakken Volcanic Province (Well 7316/5-1), the upper Pliocene section is sampled with sidewall cores. In Wells 7117/9-1 and 7117/9-2 on the Senja Ridge, only ditch cuttings were available. The upper Pliocene deposits in Wells 7316/5-1, 7117/9-1, and 7117/9-2 lack any definitive age control, and dating is based solely on planktonic and benthic foraminifers, supported by lithostratigraphic correlation and strontium isotope stratigraphy. Numerous terrestrial outcrops of shallow-water Pliocene marine deposits occur throughout the Arctic (e.g., Brouwers et al., 1991; Brigham-Grette and Carter, 1992; Feyling-Hanssen, 1976, 1980, 1990; Feyling-Hanssen et al., 1982; Funder et al., 1985; Todd, 1957; Vincent et al., 1984). These outcrop sections also lack definitive age control. They are normally correlated either by means of amino-acid racemization values or by macro- or microfaunal fossil assemblages. Most of these localities represent isolated sections of the Pliocene, which may or may not be correlative (Osterman, 1996).

At Hole 986D, calcareous benthic foraminifers are found in 82% of the samples in the interval between Sample 162-986D-28R-1, 30–36 cm (647.72 mbsf), and 54R-1, 29–36 cm (897.62 mbsf). The interval from 897.62 mbsf to the bottom of the hole (Sample 162-986D-60R-1, 29–36 cm, 955.32 mbsf) is barren. Calcareous benthic foraminifers are found at most of the same levels as planktonic foraminifers, and additionally at a few other levels. As with the planktonic foraminifers, the benthic assemblage in this 250-m-thick interval exhibits highly variable abundance, fluctuating frequently from abundant to rare or barren. Contrary to the planktonic foraminifers, the tests of certain species are broken, worn, or corroded. However, most species that constitute the assemblage occur uniformly throughout the section. Consequently, only one assemblage zone is defined; namely the *Melonis zaandamae–Cassidulina teretis* Zone.

Tests of the nominate species occur quite frequently throughout the succession. Other important taxa are *Pullenia subcarinata*, *Cassidulina reniforme*, *Epistominella exigua*, *Epistominella* spp., *Pullenia bulloides*, and *Cibicides lobatulus* (Fig. 4). Other characteristic forms that occur more sporadically include *Buccella tenerrima*, *Elphidium excavatum*, *Elphidium* spp., *Elphidium albiumbilicatum*, *Angulogerina angulosa*, *Quinqueloculina seminulum*, *Buccella frigida*, *Virgulina loeblichi*, *Triloculina* sp., *Angulogerina fluens*, *Cibi-*

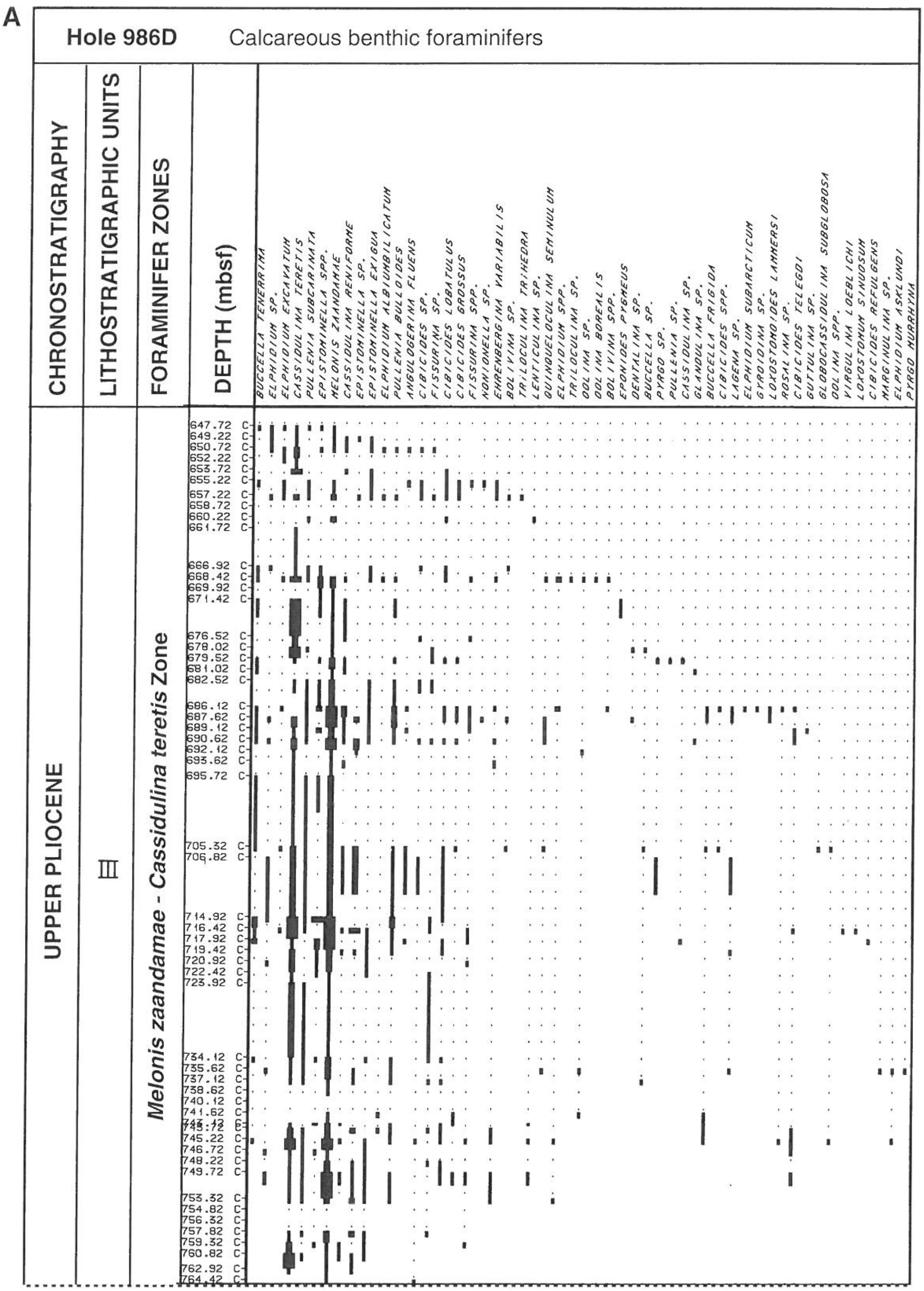

Figure 4. **A.** Range chart of upper Pliocene calcareous benthic foraminifers in Hole 986D (upper part of investigated section). See Figure 3 for explanation of symbols. (Continued on next page.)

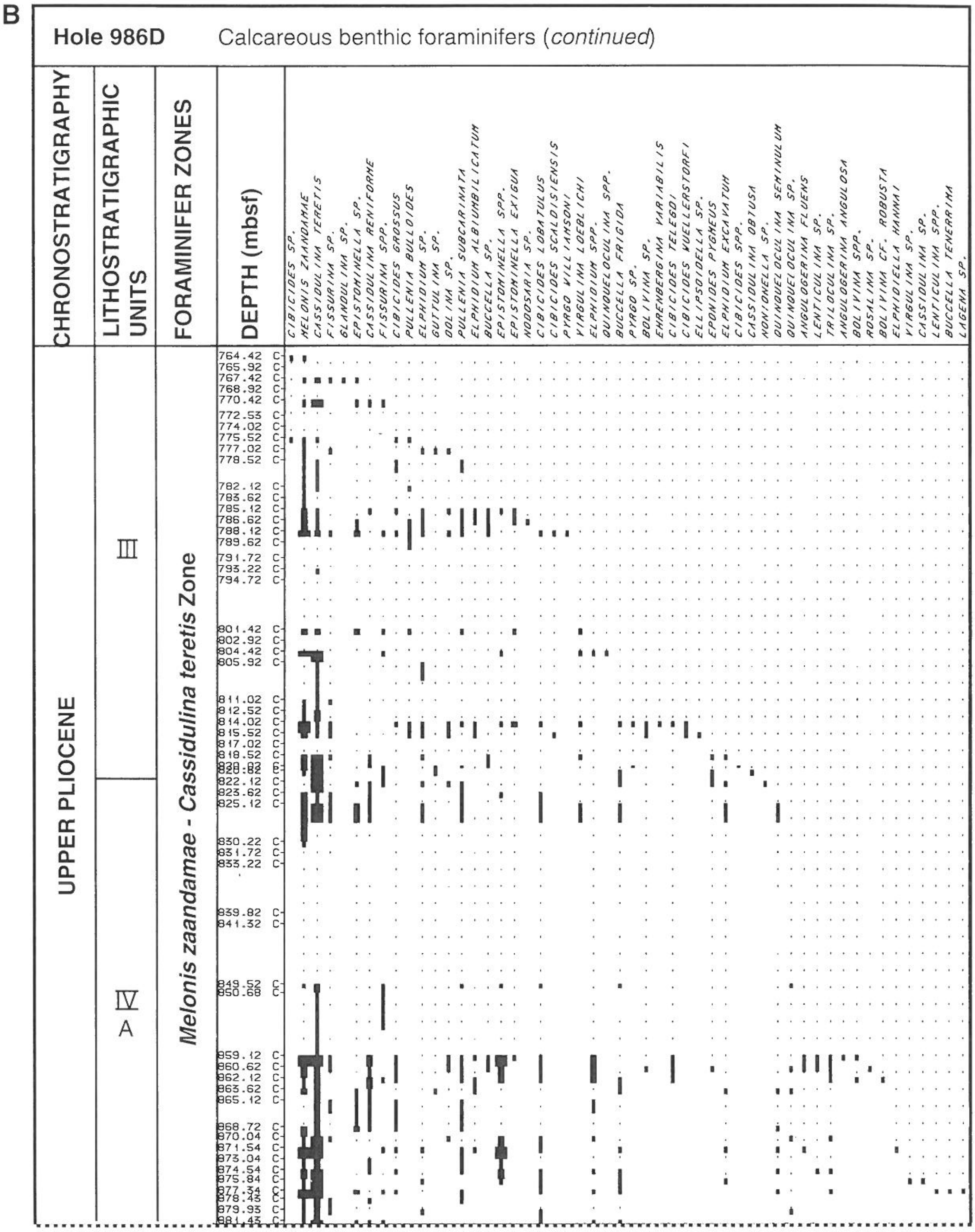

Figure 4 (continued). **B.** Range chart of upper Pliocene calcareous benthic foraminifers in Hole 986D (middle part of investigated section).

cides grossus, *Elphidiella hannai* (one specimen at 871.54 mbsf), *Ehrenbergina variabilis*, *Cibicides telegdi*, and *Eponides pygmeus*.

With the exception of *C. grossus*, *E. hannai*, *E. variabilis*, *C. telegdi*, and *E. pygmeus*, all the calcareous benthic foraminifers are extant species. *E. variabilis*, *C. telegdi*, and *E. pygmeus* are probably reworked from Oligocene or Miocene deposits (Ulleberg, 1974; Stratlab, 1988; Gradstein and Bäckström, 1996; Eidvin et al., 1998a). *C. grossus* and *E. hannai* are known from upper Pliocene deposits in the western Barents Sea (Eidvin et al., 1993a, 1998b), from the Norwegian Sea continental shelf (Eidvin and Riis, 1991; Eidvin et al., 1998a; Poole and Vorren, 1993; Stratlab, 1988), and in the North Sea (King, 1989; Knudsen and Asbjörndottir, 1991; Eidvin and Riis, 1992; Eidvin et al., 1993b; Pedersen, 1995). *C. grossus* is, however, recorded in deposits as old as the late Miocene in the Netherlands. *E.*

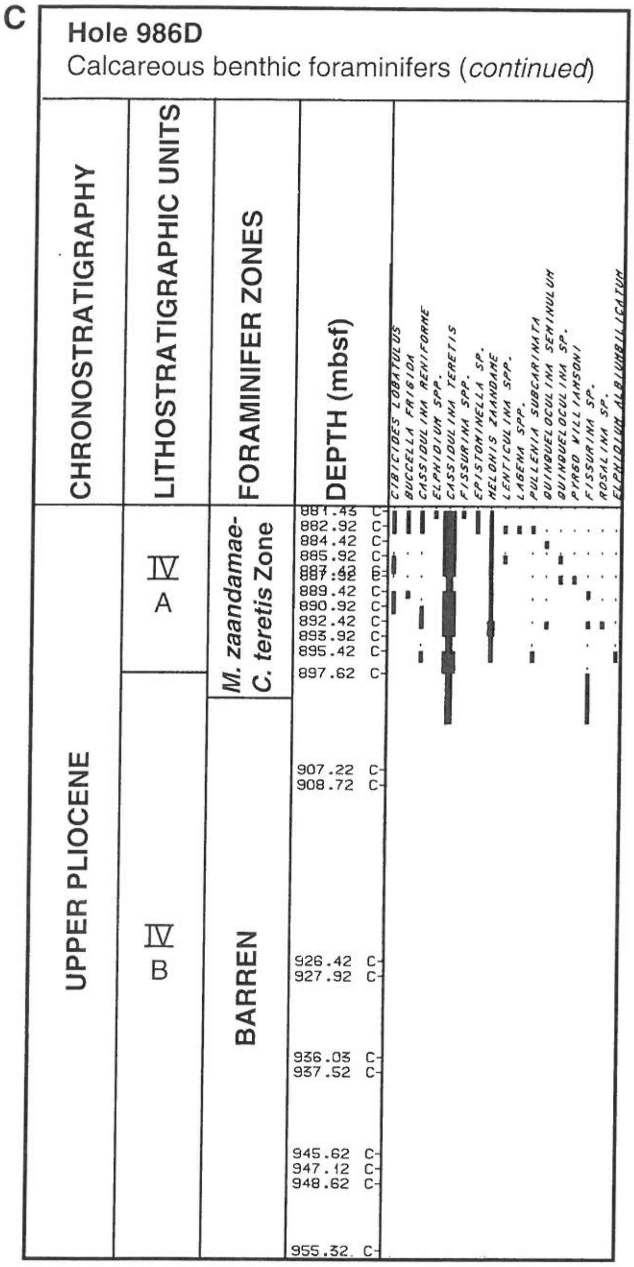

Figure 4 (continued). **C.** Range chart of upper Pliocene calcareous benthic foraminifers in Hole 986D (lower part of investigated section).

hannai is known from upper Pliocene deposits in the same area (Doppert, 1980). The single recorded specimen of *E. hannai* may represent contamination.

Species of *Elphidium* are typically restricted to shallow water and often occur in proximal glaciomarine environments. Therefore, it is possible that most of the *Elphidium* specimens have been ice rafted into these water depths (Osterman, 1984, 1996) or transported by sedimentary mass-flow processes. *A. angulosa*, *E. hannai*, *C. lobatulus*, *A. fluens*, *V. loeblichi*, and *C. grossus* are also probably reworked from shallower water environments (Mackensen et al., 1985; Skarbø and Verdenius, 1986). The origin of some other specimens is not as clear. Many specimens of *C. teretis* and some tests of *N. affine* are worn or broken. Both of these species have a wide water-depth range. Many of these specimens are probably in situ, but some of the broken

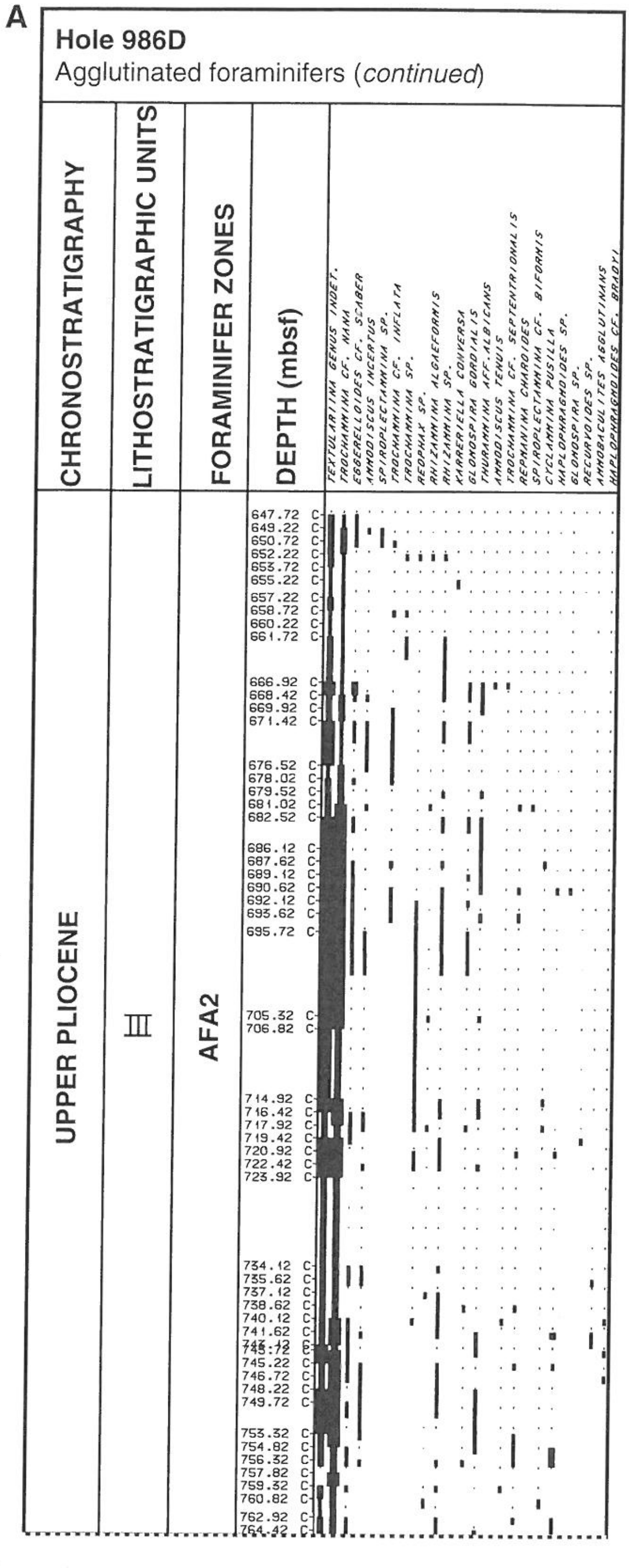

Figure 5. **A.** Range chart of upper Pliocene agglutinated foraminifers in Hole 986D (upper part of investigated section). See Figure 3 for explanation of symbols. (Continued on next page.)

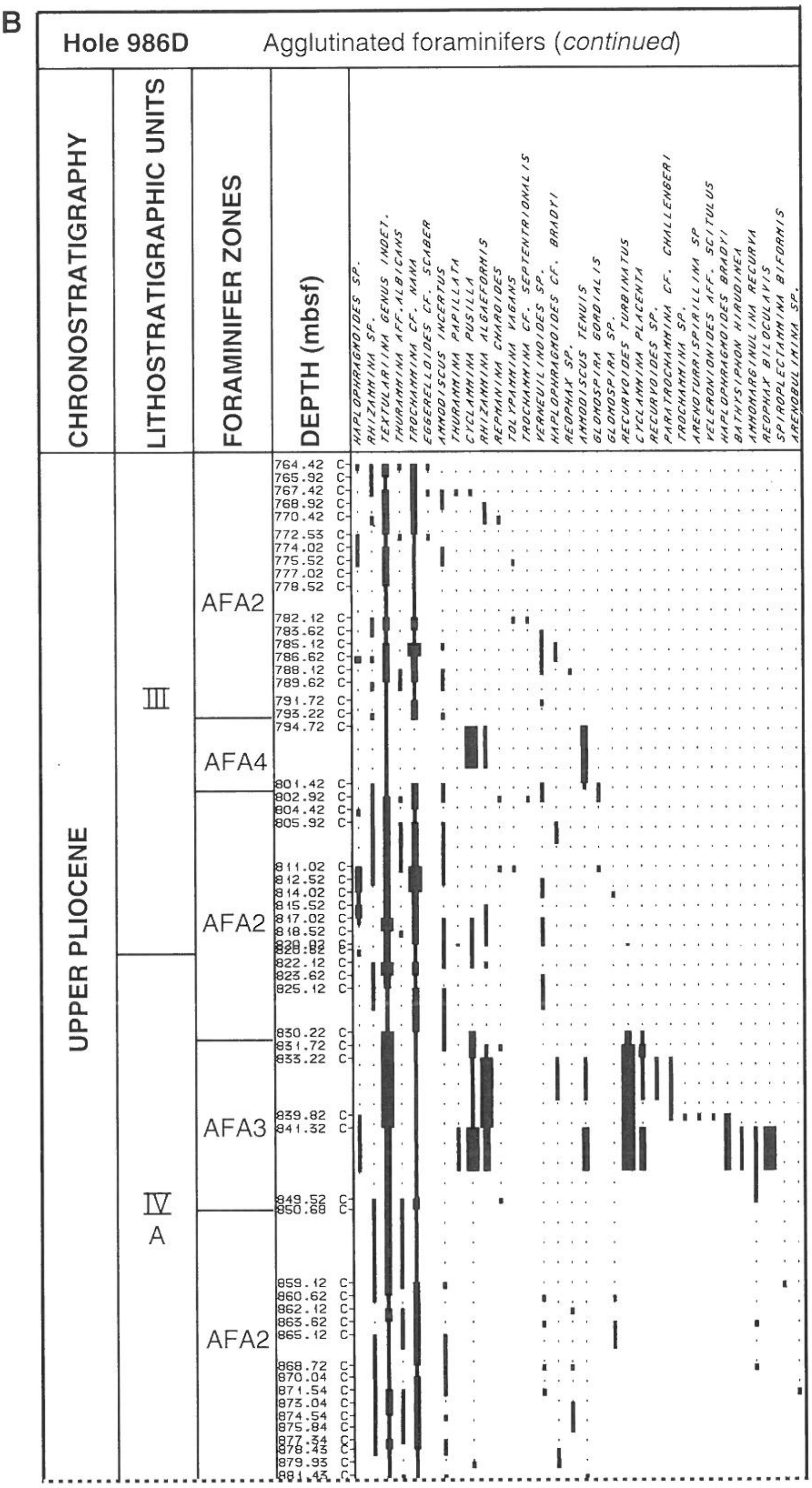

Figure 5 (continued). **B.** Range chart of upper Pliocene agglutinated foraminifers in Hole 986D (middle part of investigated section).

C

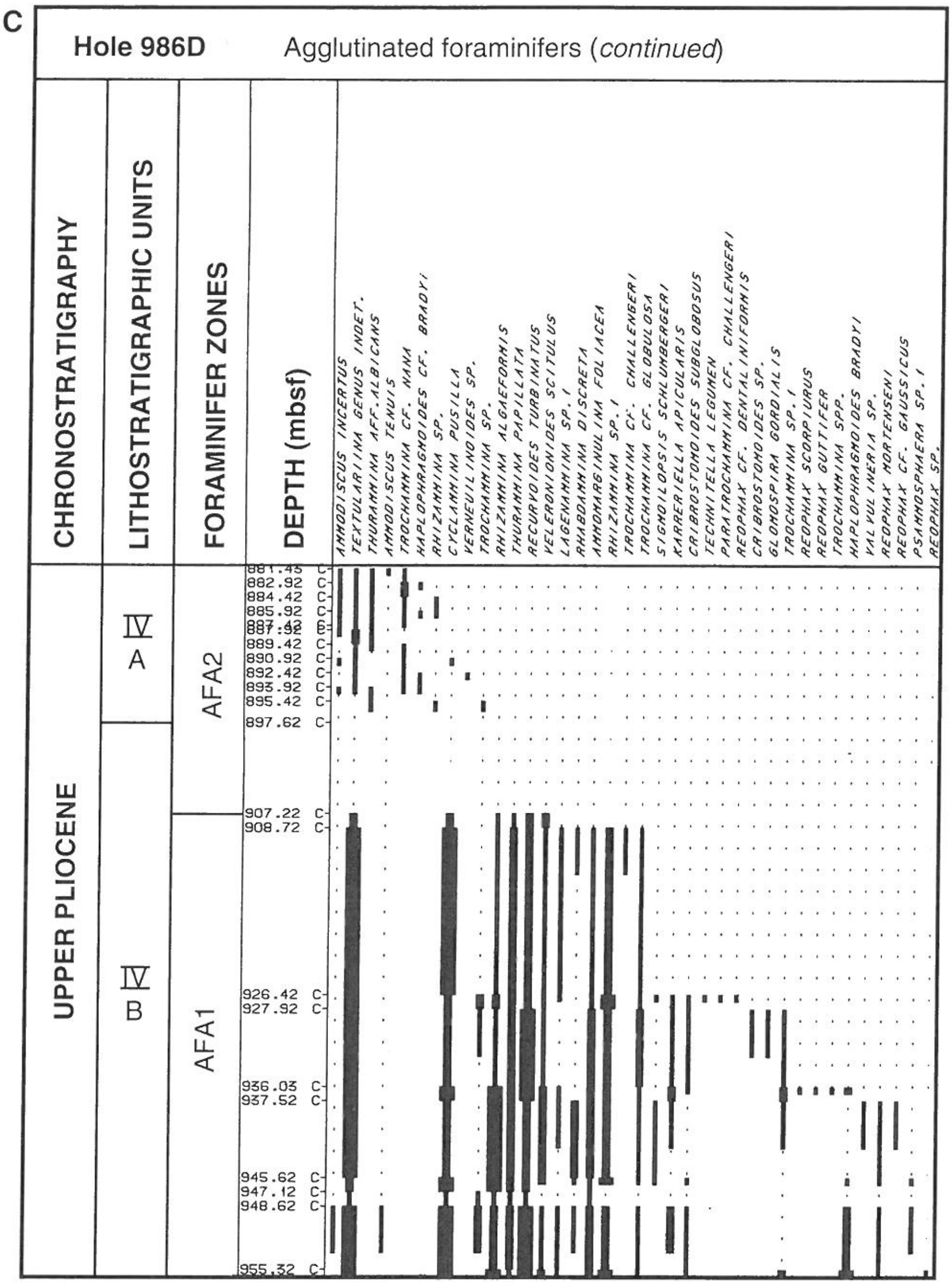

Figure 5 (continued). **C.** Range chart of upper Pliocene agglutinated foraminifers in Hole 986D (lower part of investigated section).

tests might have been reworked from shallower water-depth environments (Mackensen et al., 1985). *E. exigua*, *P. bulloides*, *P. subcarinata*, *Triloculina trihedra*, *Pyrgo murrhina*, and *Cibicides wuellerstorfi* are all deep-water forms (Sejrup et al., 1981; Mackensen et al., 1985; Skarbø and Verdenius, 1986).

In samples containing calcareous benthic foraminifers, the number of species ranges from one to 25 and the number of specimens (per cubic centimeter sediment) from one to 20. An overall low number of species and specimens in this succession indicates a generally cold oceanic climatic regime. Samples that are barren or have low diversities of calcareous foraminifers probably represent episodes of severe glaciation. Samples containing faunas with comparatively high diversities suggest warmer episodes (Osterman, 1996). This interpretation is consistent with the varying contents of Arctic species such as *E. excavatum* f. *clavata*, *C. reniforme*, *V. loeblichi*, *Elphidium subarcticum*, and *Elphidium asklundi* as well as with changing amounts of boreal species, including *A. angulosa*, *C. teretis*, *Bolivina* cf. *robusta*, *E. exigua*, and *E. albiumbilicatum* (Feyling-Hanssen, 1983). However, the presence of reworked forms introduces some uncertainties into this interpretation.

AGGLUTINATED FORAMINIFERAL BIOSTRATIGRAPHY

Main Faunal Features

Agglutinated foraminifers occur in varying amounts in all the analyzed samples from 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 60R-1, 29–36 cm (955.32 mbsf), as shown in Figure 5. Within this interval, four agglutinated foraminiferal assemblages (AFA) are distinguished. The preservation of the assemblages varies from dominantly porous noncompressed through mixed to dominantly

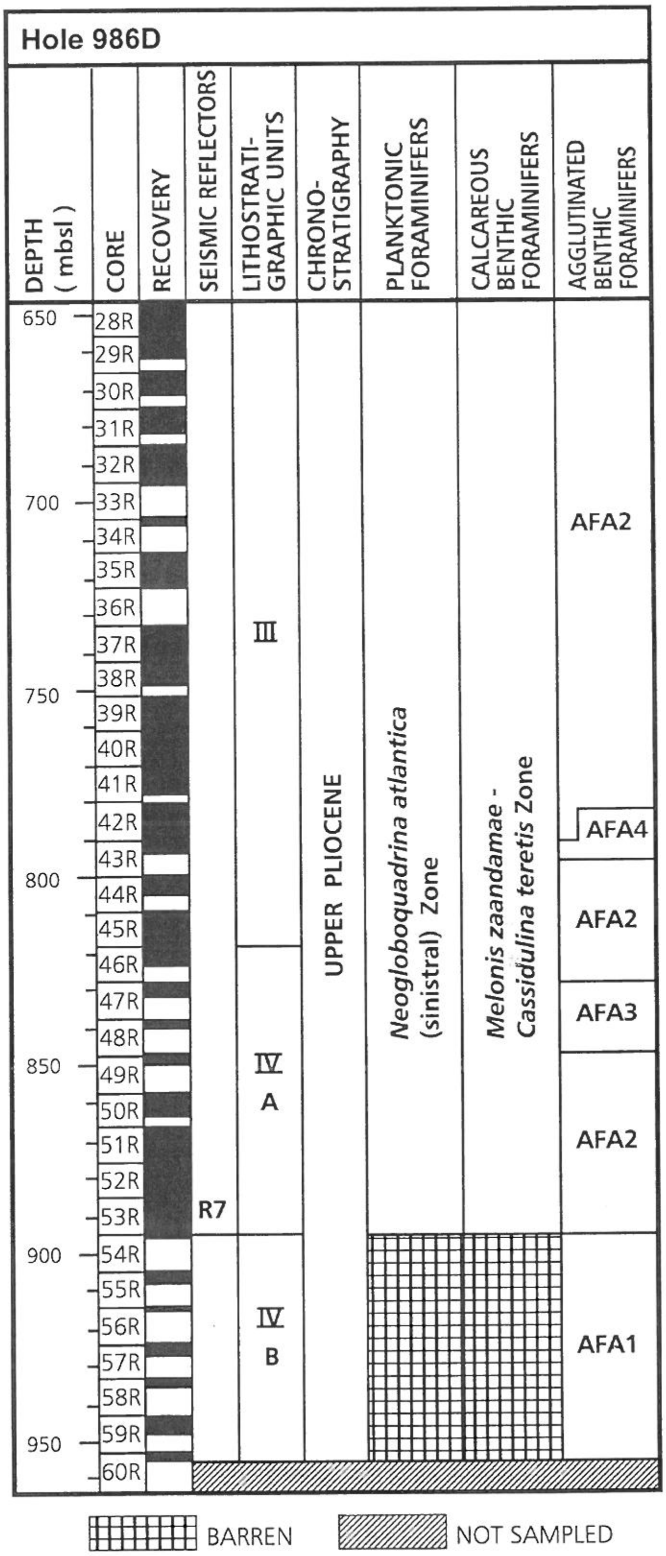

Figure 6. Zonal scheme of the analyzed upper Pliocene section in Hole 986D based on the three main foraminifer groups (AFA = agglutinated foraminiferal assemblage).

silicified compressed. These preservational types occur in repeated units of changing thicknesses throughout the analyzed succession. Based on this distribution pattern, 14 preservational units (PU) are distinguished (Fig. 7).

The porous noncompressed faunal component is composed of specimens showing the original shape of the chambers (which usually are empty) and the slightly porous texture of unaltered agglutinated tests. In the silicified compressed component, the tests are flattened to disappearance of the chamber cavities. Owing to diagenetic silicification, the silt grains forming the walls are no longer discernible.

Agglutinated Assemblages

AFA1, Cyclammina pusilla *assemblage*

This fauna describes the lowermost part of the cored section from Sample 162-986D-60R-1, 29–36 (955.32 mbsf), through 55R-1, 24–31 cm (907.22 mbsf). It is dominated by *Cyclammina pusilla*, *Recurvoides turbinatus*, *Rhizammina* sp., and *Thurammina papillata*. Characteristic species include *Rhizammina algaeformis*, *Verneuilinoides scitulus*, *Ammomarginulina foliacea*, *Karreriella apicularis*, and *Reophax mortenseni*. Owing to the poor state of preservation, a large number of specimens could not be identified at the generic level and are designated as *Textulariina* genus indeterminate on the range chart (Fig. 5). Based on its composition and preservational features, the assemblage is interpreted to represent a bathyal in situ fauna. It is identical to the porous noncompressed interval PU1 (Fig. 7).

AFA2, Trochammina *cf.* nana *assemblage*

This assemblage comprises three intervals characterized by silicified compressed taxa or mixed faunas. It is subdivided into a lower, middle, and thick upper segment by two intervening porous noncompressed assemblages (Fig. 5). *Trochammina* cf. *nana is* dominant through each of the three segments. The undifferentiated group, *Textulariina* genus indeterminate, is also quantitatively important. The assemblage is interpreted to consist mainly of redeposited specimens.

The lower *T.* cf. *nana* assemblage extends from Sample 162-986D-54R-1, 29–36 cm (897.62 mbsf), through 49R-1, 29–36 cm (849.52 mbsf). Characteristic species include *Ammodiscus incertus*, *Rhizammina* sp., and *Thurammina* aff. *albicans* in addition to more sporadic occurrences of *Glomospirella* sp., *Haplophragmoides* cf. *bradyi*, and *Verneuilinoides* sp. This assemblage segment corresponds to the silicified compressed interval PU2.

The middle segment characterized by this assemblage extends from Sample 162-986D-46R-4, 29–36 cm (825.12 mbsf), to 44R-1, 29–36 cm (801.42 mbsf). Besides the dominant forms, significant taxa include *A. incertus*, *Rhizammina* sp. *T.* aff. *albicans*, *Haplopragmoides* sp., and *Verneuilinoides* sp. This segment contains the silicified compressed intervals PU4 and PU6 as well as the mixed interval PU5.

The upper part of the *T.* cf. *nana* assemblage extends from Sample 162-986D-43R-2, 29–36 cm (793.22 mbsf), through 28R-1, 30–36 cm (647.72 mbsf). Thus, it makes up almost half of the upper Pliocene part of the cored section. Characteristic, but quantitatively subordinate, species include *Eggerelloides* cf. *scaber*, *A. incertus*, *Rhizammina* sp., and *T.* cf. *albicans*. Many taxa, such as *Glomospira gordialis*, *Repmanina charoides*, *C. pusilla*, and *Haplophragmoides* sp., occur in low numbers restricted to scattered samples. Within this segment, seven preservational units are distinguished. Four of these are of the silicified compressed type (PU8, PU10, PU12, and PU14), whereas three are of mixed nature (PU9, PU11, and PU13).

AFA3, Recurvoides turbinatus *assemblage*

This assemblage is developed from Sample 162-986D-48R-2, 29–36 cm (841.32 mbsf), through 47R-1, 29–36 cm (830.22 mbsf).

AGGLUTINATED FORAMINIFER ASSEMBLAGES		AGGLUTINATED FORAMINIFER PRESERVATIONAL UNITS		SILICIFIED COM - PRESSED TESTS %		
				0 - 25	25-75	75-100
AFA2	*Trochammina* cf. *nana*	PU 14	162-986D-28R-01(647.72 mbsf) Silicified compressed 162-986D-28R-04(652.22 mbsf)			▨
		PU 13	162-986D-28R-05(653.72 mbsf) Mixed 162-986D-29R-02(658.22 mbsf)		▨	
		PU 12	162-986D-29R-03(660.22 mbsf) Silicified compressed 162-986D-34R-02(706.82 mbsf)			▨
		PU 11	162-986D-35R-01(714.92 mbsf) Mixed		▨	
		PU 10	162-986D-35R-02(716.42 mbsf) Silicified compressed 162-986D-40R-03(765.92 mbsf)			▨
		PU9	162-986D-40R-04(767.42 mbsf) Mixed 162-986D-40R-06(770.42 mbsf)		▨	
		PU8	162-986D-41R-01(772.53 mbsf) Silicified compressed 162-986D-43R-02(793.22 mbsf)			▨
AFA4	*Ammodiscus tenuis*	PU7	162-986D-43R-03(794.72 mbsf) Porous non-compressed	▨		
AFA2	*Trochammina* cf. *nana*	PU6	162-986D-44R-01(801.42 mbsf) Silicified compressed 162-986D-45R-05(817.02 mbsf)			▨
		PU5	162-986D-45R-06(818.52 mbsf) Mixed 162-986D-46R-02(822.12 mbsf)		▨	
		PU4	162-986D-46R-03(823.52 mbsf) Silicified compressed 162-986D-46R-04(825.12 mbsf)			▨
AFA3	*Recurvoides turbinatus*	PU3	162-986D-47R-01(830.22 mbsf) Porous noncompressed 162-986D-48R-02(841.32 mbsf)	▨		
AFA2	*Trochammina* cf. *nana*	PU2	162-986D-49R-01(849.22 mbsf) Silicified compressed 162-986D-54R-01(897.62 mbsf)			▨
AFA1	*Cyclammina pusilla*	PU1	162-986D-55R-01(907.22 mbsf) Porous noncompressed 162-986D-60R-01(955.32 mbsf)	▨		

RLN 9707010

Figure 7. Agglutinated foraminiferal assemblages and preservational units in the upper Pliocene succession in Hole 986D (AFA = agglutinated foraminiferal assemblage, PU = preservational units).

In addition to the nominate species, the unit is dominated by *R. algaeformis* and *C. pusilla*. *Textulariina* genus indet. is quantitatively important, whereas the frequency of *C.* cf. *nana* is strongly reduced. Characteristic species are *Cyclammina trullissata*, *Paratrochammina* cf. *challengeri*, *Haplophragmoides bradyi*, *Bathysiphon hirudinea*, and *Reophax bilocularis*. The assemblage is a porous noncompressed type, corresponding to the interval PU3.

AFA4, Ammodiscus tenuis *assemblage*

This is recognized only in Sample 162-986D-43R-3, 29–36 cm (794.72 mbsf), strongly dominated by *C. pusilla* and characterized by *A. tenuis* and *R. algaeformis*. The fauna is of porous noncompressed preservation designated as PU7.

DEPOSITIONAL SIGNIFICANCE OF PRESERVATIONAL UNITS

Porous Noncompressed Faunal Units

In the samples referred to in these preservational units, 75%–100% of the specimens are classified as porous noncompressed. Both small and large specimens are present, although large tubular forms commonly dominate. The porous wall texture indicates that no significant diagenetic cementation of the agglutinated material has taken place. The tests retain their original shape with no, or only very weak, compressional deformation. In most species the color is white or yellowish, but some are reddish or light brown.

The generally well-preserved nature of the assemblages suggests that they have not been significantly affected by post-mortem transport and resedimentation processes. In accordance with this, the taxonomic composition of the faunas indicates bathyal to abyssal conditions and is consistent with a late Pliocene age.

Tubular taxa are abundant in the *Cyclammina pusilla* assemblage, common in the *Recurvoides turbinatus* assemblage, and are present in low numbers in the *Ammodiscus tenuis* assemblage. The group is generally regarded to be characteristic of deep-water, mainly bathyal environments (Gradstein and Berggren, 1981; Miller et al., 1982; Jones, 1988; Gradstein and Bäckström, 1996). In the *C. pusilla* assemblage, the tubular group is represented by *Rhizammina algaeformis*, *Rhabdammina discreta*, and *Rhizammina* sp., whereas in the *R. turbinatus* assemblage, *R. algaeformis* is dominant. As shown by Schröder (1986), *R. algaeformis* is abundant in modern bathyal to abyssal faunas of the northwestern Atlantic Ocean (Nova Scotia Rise, Bermuda Rise, and Nares Abyssal Plain). On the Nova Scotia Rise, *R. discreta* occurs mainly in the depth interval 2750–3550 m.

According to information published by Schröder (1986), Charnock and Jones (1990), and Jones (1994), the following species of the porous noncompressed assemblages are generally confined to bathyal and greater depths in the present-day North Atlantic Ocean: *Ammodiscus tenuis*, *Cyclammina pusilla*, *Thurammina papillata*, *Recurvoides turbinatus*, *Haplophragmoides bradyi*, *Ammomarginulina foliacea*, *Karreriella apicularis*, *Cribrostomoides subglobosus*, *Technitella legumen*, *Reophax guttifer*, *Ammonarginulina recurva*, *Cyclammina trullissata*, and *Reophax bilocularis*.

Silicified Compressed Faunal Units

In the samples belonging to these faunal units, 75%–100% of the foraminifers show the silicified compressed type of preservation. The specimens are small in size, markedly deformed by compression, and are strongly silicified by diagenetic processes. Their color is usually gray or brownish. The poor preservation and small size of the tests made taxonomic determinations difficult, which explains the extensive use of open nomenclature.

The preservational features of this fauna suggest reworking from pre-existing strata, with subsequent transport and resedimentation in the upper Pliocene lower slope environment. The small and relatively uniform size of the tests (usually 130–200 µm) suggests sorting by a hydrodynamic process.

The redeposited faunal component is dominated by *Textulariina* genus indet. and *T.* cf. *nana*. In addition to the redeposited forms, many samples contain scattered, well-preserved tests of more or less in situ origin belonging to species such as *R. algaeformis*, *C. pusilla*, and *Repmanina charoides*.

Mixed Faunal Units

The samples grouped in the mixed units contain 25%–75% porous noncompressed specimens, whereas the rest is silicified compressed. These fauna are developed in four thin intervals between silicified compressed units (Fig. 7). The increased frequency of the in situ faunal component in the mixed assemblages suggests periods with reduced influx of material from extrabasinal sources, or increased benthic productivity within the depositional area.

DISCUSSION

There are marked similarities between the Pliocene section in Hole 986D and some of the other Pliocene-aged deposits mentioned above, in particular the *Geodia* sp.–*Globigerina bulloides* Zone (D) in Well 7117/9-1 on the Senja Ridge (Eidvin et al., 1993a) and the *Globigerina bulloides–Cassidulina teretis* Zone (BB-FB) in Well 7316/5-1 in the Vestbakken Volcanic Province (Eidvin et al., 1998b; Fig. 8). Although the foraminifer assemblages in Wells 7117/9-1 and 7316/5-1 differ somewhat from those of Hole 986D in their generally lower diversity and poorer preservation, many of the recorded species are the same. In all sections, *C. teretis* and *M. zaandamae* dominate the calcareous benthic assemblages, whereas *G. bulloides* dominates the planktonic faunas. In addition, all sections contain many reworked calcareous and agglutinated specimens from Miocene to Eocene deposits. However, the analyzed section in Hole 986D contains more benthic species of deep-water affinity.

A maximum age of 2.7 Ma is assigned to the sections in Wells 7117/9-1 and 7316/5-1, and these sections probably represent sediments deposited after the great increase in the supply of ice-dropped material at the Leg 104 sites at the Vøring Plateau (Jansen and Sjøholm, 1991; Eidvin et al., 1993a, 1998b). A minimum age of 2.4 Ma is based on the fact that *G. bulloides* is common in Pliocene sediments older than 2.4 Ma at the Vøring Plateau sites (Spiegler and Jansen, 1989). However, *G. bulloides* is also found in the warmest interglacials of the last 1 Ma (Kellogg, 1977).

The assemblages in Hole 986D also have a strong affinity with the faunas recorded from the section between 151.27 and 502.97 mbsf in Hole 910C (Leg 141). This section also has a benthic assemblage with *C. grossus* (Osterman, 1996) and common *C. teretis*, *M. zaandamae*, and *Epistominella* associated with rare *E. albiumbilicatum*. The planktonic assemblage is dominated by *N. atlantica* (sin.) and *G. bulloides*. Paleomagnetic and fossil evidence date this section to the late Pliocene. A maximum age of 2.7 Ma is assigned to the base of the section (Spiegler, 1996; Fig. 8).

The interval in between Sample 104-643A-7H-2, 74–78 cm, and 7H-5, 74–78 cm, on the Vøring Plateau also contains common *C. teretis*, *M. zaandamae*, *N. atlantica* (sin.), and *G. bulloides*. Paleomagnetic records date this section from latest early Pliocene to earliest late Pliocene (Spiegler and Jansen, 1989; Osterman and Qvale, 1989; Fig. 8).

According to Channell et al. (Chap. 10, this volume), the uppermost 150 m at Site 986 appears to record the Brunhes/Matuyama boundary and the Jaramillo Subchron. The base of the drilled section (at ~950 mbsf) is interpreted to lie within the Matuyama Chron (age <2.58 Ma) with the normal polarity interval (interpreted as the Olduvai Subchron) occurring from ~730 to 750 mbsf. The age of the Olduvai Subchron is 1.76–1.98 Ma according to Cande and Kent (1992). This implies that the LO of *N. atlantica* (sin.) and the last common occurrence of *G. bulloides* are <1.7 Ma. In other words, this results in an apparent discrepancy of 0.7 m.y. at Site 986 compared to other ODP/Deep Sea Drilling Project Sites in the Norwegian Sea or the North Atlantic. This discrepancy is especially unlikely for the transitional dwelling *G. bulloides*. Extensive reworking of planktonic foraminifers at Site 986 could explain this problem, but few of the tests show any sign of wear. Less than 200 k.y. is an extremely short time to deposit the analyzed section. However, such extreme accumulation rates, in the 2.7–2.4 Ma time interval, are recorded from the western margin of the Barents Shelf (Eidvin et al., 1993a, 1998b), the Norwegian Sea continental shelf (Eidvin et al., 1998a), and the northern North Sea (Eidvin and Riis, 1992). For the time being, we are unable to find a solution on the mentioned discrepancy between the paleomagnetic and biostratigraphic data.

The porous noncompressed assemblages observed between 907.22 and 955.32 mbsf, between 830.22 and 841.32 mbsf, and at 794.72 mbsf consist exclusively of agglutinated taxa. The absence of calcareous benthic and planktonic foraminifers from these intervals indicates that the deposition of the assemblages has taken place most likely below the local carbonate compensation depth, although diagenetic dissolution of carbonate cannot be totally excluded.

The four silicified compressed assemblages and the seven mixed agglutinated assemblages are associated with a calcareous faunal component consisting of relatively few benthic specimens and more

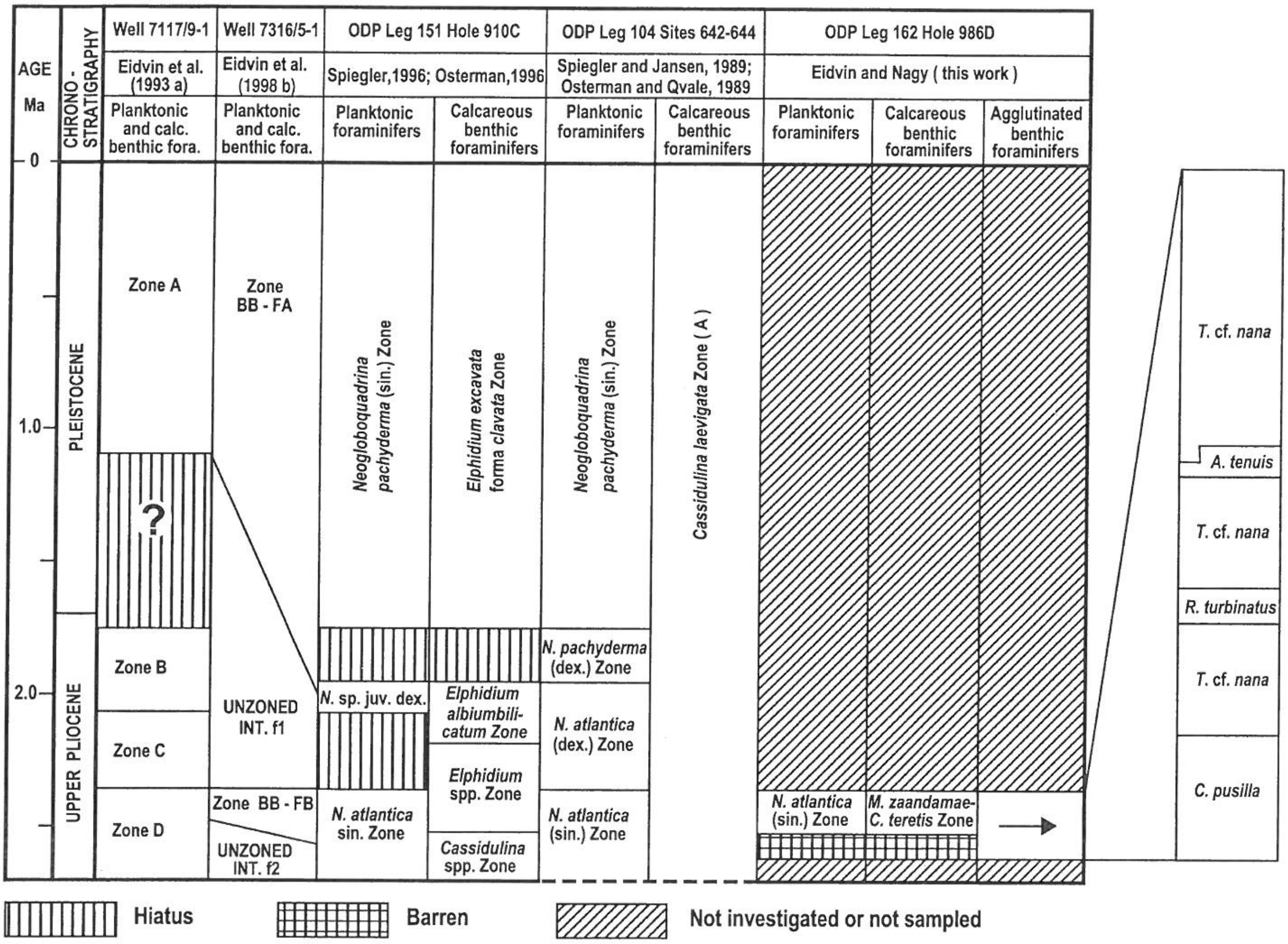

Figure 8. Correlation chart of upper Pliocene and Pleistocene foraminifer stratigraphic units in sections located in the Norwegian-Greenland Sea and the Barents Sea.

common planktonic taxa. It seems also likely that the calcareous benthic component is at least partly reworked, as suggested by the common occurrences of broken specimens.

SUMMARY

The studied interval from 647.72 to 955.32 mbsf in Hole 986D contains the following stratigraphic units based on foraminifers: the planktonic *Neogloboquadrina atlantica* (sinistral) Zone, the benthic *Melonis zaandamae–Cassidulina teretis* Zone, and four agglutinated assemblages designated as AFA1 through AFA4. The lowermost 55 m of the interval are barren of planktonic and calcareous benthic foraminifers but contain varying amounts of agglutinated taxa (Fig. 6).

Paleomagnetic data show that the bottom of the hole is in the Matuyama Chron, which implies an age of <2.6 Ma (Channell et al., Chap. 10, this volume). The occurrence of *N. atlantica* (sin.) implies an age not younger than 2.4 Ma for the top of the interval. The paleomagnetic data indicate a maximum age of ~1.7 Ma for the top of the interval (Channell et al., Chap. 10, this volume) and show a discrepancy between the paleomagnetic and the biostratigraphic data in this part of the hole.

A strongly variable abundance of planktonic and calcareous benthic foraminifers indicates alternating glacial and interglacial conditions. The planktonic fauna suggests a generally cold ocean with short warm to transitional surface-water ingressions and is consistent with the changing content of calcareous benthic Arctic and boreal species. Most of the planktonic specimens are well preserved and show no sign of having been reworked. Many of the calcareous benthic specimens, however, are broken, indicating considerable reworking.

The planktonic and calcareous benthic assemblages are correlated with similar faunas in Hole 910C on the Yermak Plateau, Hole 643A on the Vøring Plateau, the exploration Well 7117/9-1 on the Senja Ridge, and the exploration Well 7316/5-1 in the Vestbakken Volcanic Province.

The agglutinated assemblages represent alternating porous noncompressed bathyal in situ faunas and silicified compressed redeposited taxa as well as mixed faunas of in situ and redeposited specimens (see Fig. 7). The exclusively agglutinated assemblages occurring in three segments of Hole 966D indicate that the deposition has taken place below the local carbonate compensation depth.

ACKNOWLEDGMENTS

The authors extend their thanks to Sigrun Torrissen, Gabriella Nagy, Sigmund K. Runestad, Finn Moe, and Linn M. Johansen for their careful and accurate technical assistance and to Rune Goa and Per Torgersen for preparation of the illustrations. They also thank Paul Grogan, Eystein Jansen, Anders Solheim, and Robert Williams for useful discussions and suggestions.

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Date of initial receipt: 25 August 1997
Date of acceptance: 15 April 1998
Ms 162SR-009